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# Mitigation Options for Human Settlements

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# EXECUTIVE SUMMARY

This chapter provides a summary of current knowledge of options for reducing the emissions of greenhouse gases (GHGs) in human settlements. The largest portion of GHG emissions in human settlements is in the form of carbon dioxide ($CO_2$) from energy use in buildings (including emissions from power plants that produce electricity for buildings), amounting to about 1.7 billion tons of carbon. The other three major sources of GHG emissions are methane from urban solid waste (equivalent to 135–275 million tons of carbon in the form of $CO_2$), methane from domestic and industrial wastewater (200–275 million tons of carbon equivalent), and a variety of GHGs produced through the combustion of biomass in cookstoves throughout the developing world (estimated to be 100 million tons of carbon equivalent). This chapter does not cover $CO_2$ emissions from the combustion of biomass; this complex topic is treated in Chapters 15 and 24.

Regarding $CO_2$, we note the following:

- Residential buildings contributed 19% of total global emissions of $CO_2$ in 1990.
- Commercial buildings contributed an additional 10% of total global emissions of $CO_2$ in 1990.
- Industrial (primarily OECD) countries produced 63% of global $CO_2$ emissions in 1990; 19% came from the former Soviet Union and Eastern Europe and 18% from the developing world.
- Overall growth in emissions of $CO_2$ from buildings was slightly over 1% per year from 1973 to 1990. Almost all of this growth took place in the developing world and in the former Soviet Union and Eastern Europe.

## Key Factors Affecting the Growth of Greenhouse Emissions

The potential for the greatest growth in $CO_2$ emissions—in both percentage and absolute terms—is in the developing world, where per capita energy consumption in human settlements is very low. Even in the industrialized countries, however, if policies to minimize such emissions are not enacted and rigorously carried out, the already high levels of $CO_2$ emissions can increase. The most significant factors influencing the growth of GHG emissions in human settlements are likely to be efficiency of energy use, carbon intensity of fuels used directly in human settlements or to produce electricity, population growth, the nature of development in the developing world, the nature and rate of global economic growth, and implementation of policies that are directed toward fulfilling national commitments to reducing GHG emissions.

## Technical and Economic Potential for Reducing GHG Emissions

Many cost-effective technologies are available to reduce energy consumption and hence $CO_2$ emissions. Some examples include more efficient space-conditioning systems; improved insulation and reduced air leakage in windows, walls, and roofs—leading to reduced heat losses; and more efficient lighting and appliances (refrigerators, water heaters, cook stoves, etc.). In addition, measures to counter trends toward higher ambient temperatures in urban areas through increased vegetation and greater reflectivity of roofing and siding materials can yield significant reductions in space-cooling energy requirements in warm climates. Finally, technologies for capturing methane gases and converting them to useful purposes exist and are cost-effective in many applications. Other technologies that can reduce or prevent the formation of methane (e.g., in landfills) are also increasingly available.

## Policy Options

Policy options for reducing the growth of carbon emissions from human settlements include energy pricing strategies, regulatory programs, utility demand-side management programs, demonstration and commercialization programs, and research and development. Each type of program has been carried out, primarily in industrialized countries, and many have achieved significant energy savings.

Because there has been considerable experience with these policies in many industrialized countries and because the technical and economic potential for energy savings is still high even after many years of improved energy efficiency, improvements in energy efficiency will be possible for many years. The developing world has even greater opportunities to improve energy efficiency. However, resources need to be made available (especially collaborations in training activities and institution building) so that these countries can develop the expertise to bring about higher efficiency.

## Energy Scenarios: Potential Impacts of Energy Efficiency

Many "business-as-usual" energy scenarios postulate a 2% annual growth in buildings' energy use—much like that observed during the past several decades. Under the assumption that developing-country economies continue their growth at current rates and that industrialized economies continue their

growth at a slower rate than in the past, this 2% annual growth in energy use in buildings assumes significant continued improvement in energy efficiency.

Aggressive energy-efficiency scenarios for buildings show reductions in overall energy demand growth of 0.5 to 1.0% per year. Over 35 years (1990 to 2025), a 2% annual growth rate leads to a doubling of energy use; 1.5% per year leads to a 68% increase; and 1% per year leads to a 42% increase. Thus, energy efficiency alone could contribute about half of the reductions needed to maintain 1990 levels of $CO_2$ emissions. Such energy efficiency scenarios, however, will require strong and significant policy measures, well beyond what has been adopted to date. In addition to energy and economic policies, the growth of $CO_2$ emissions will also depend critically on worldwide population growth.

During the same period (through 2025), technologies for control of methane emissions from landfills and wastewater can achieve relative emissions reductions comparable to those of energy-efficiency measures.

Scenarios for the longer term that are aimed at increasing the efficiency of energy use while providing needed energy services suggest that radical transformations in the ways energy is used are possible. A plausible case can be made for a society that meets human needs and aspirations that is not nearly as energy and resource intensive as today's society.

## 22.1. Introduction

We define human settlements as cities, towns, villages, and even sparsely settled rural dwellings and collections of dwellings. We are concerned with GHG emissions attributable to $CO_2$ emissions resulting from the production and distribution of fossil fuel and electricity needed for all energy-using activities that take place within residential buildings, $CO_2$ emissions from energy use in commercial buildings, and the release of methane gas to the atmosphere by processes currently used for waste disposal. This chapter excludes all transport and industrial sources of GHG emissions because these are treated in other chapters.

First we describe the nature of GHG emissions from human settlements to better understand what actions could stabilize or reduce these emissions. Next we review estimates of GHG emissions from human settlements; describe the key factors that affect the growth of these emissions; assess the technical and economic potential for reducing these emissions; and describe policy measures at the local, national, and international levels that can help reduce emissions. We have grouped countries into three categories: industrialized countries (OECD and several newly industrialized countries), the former Soviet Union and Eastern Europe (FSU/EE), and developing countries.

## 22.2. Historic Trends in GHG Emissions from Human Settlements

Carbon dioxide from energy use in buildings amounts to about 1.7 billion tons of carbon. The other three major sources of GHG emissions are methane from urban solid waste (equivalent to 135–275 million tons of carbon in the form of $CO_2$), methane from domestic and industrial wastewater (200–275 million tons of carbon equivalent), and a variety of GHGs produced through the combustion of biomass in cookstoves throughout the developing world (estimated to be 100 million tons of carbon equivalent).

### 22.2.1. *$CO_2$ Emissions*

Figure 22-1 shows trends in $CO_2$ emissions associated with residential and commercial consumption of fossil fuels for the three groups of countries. The data do not include emissions of $CO_2$ from biomass fuels; although their use in the residential sector of many developing countries is considerable, past and current consumption levels are very uncertain.[1] Further, it is difficult to determine what fraction of biofuels consumption represents net emissions. The IPCC Draft Guidelines for National Greenhouse Gas Inventories require that net $CO_2$ emissions from burning biomass fuels be treated as zero because these releases are considered within the category Land-Use Change and Forestry.

The majority (63%) of (non-biomass) global $CO_2$ emissions from the residential/commercial sector in 1990 came from the
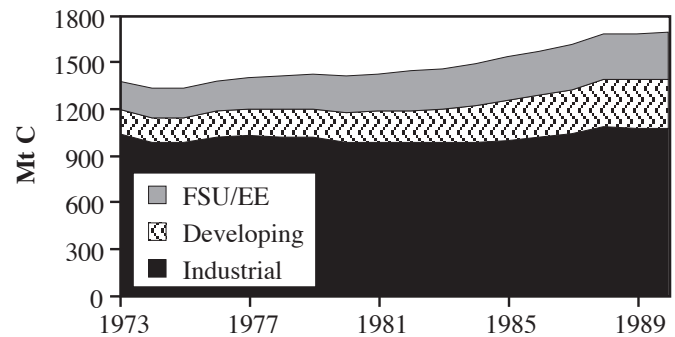


**Figure 22-1:** Global $CO_2$ emissions from residential/commercial energy consumption (Scheinbaum and Schipper, 1993; Cooper, 1993; Meyers *et al.*, 1993b).

industrialized countries. The developing countries and FSU/EE each accounted for about 19% of the total, with those shares rising since the 1970s. Whereas $CO_2$ emissions from the industrialized countries in 1990 were at approximately the same level as in 1973, emissions from the developing countries and FSU/EE have grown because of population growth and an increase in per capita levels of energy services. The growth in FSU/EE emissions reflects a change in heating technology from stoves to district heat.

Figure 22-2 shows that residential buildings account for two-thirds of total $CO_2$ emissions from buildings in nine industrialized countries. Whereas emissions from energy use in residential buildings in 1990 were slightly below their 1973 level, emissions from commercial buildings have risen. This increase reflects both the growth in floor space and the important role played by electricity.

Estimates for 12 major developing countries for 1985 show the residential sector accounting for 70% of total residential/commercial $CO_2$ emissions (Sathaye and Ketoff, 1991). Because of uncertain definitions of residential and commercial building space in developing countries, these figures are highly uncertain. The residential sector is estimated to have used 75% of final residential/commercial energy consumed in the former Soviet Union in 1988 (Cooper and Schipper, 1991).

Figure 22-2 also shows emissions for residential energy disaggregated by end-use (Scheinbaum and Schipper, 1993). Space heating accounts for more $CO_2$ emissions than any other end-use, but its share of the total has declined. Energy use for heating per square meter of living area has decreased considerably in North America and Western Europe since 1973, mainly because of improvements in existing homes and the entry of new, more energy-efficient homes and heating equipment into the stock (Schipper and Meyers, 1992). The share of electric appliances in energy consumption has grown considerably

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[1] Hall (1991) derives national estimates of biomass consumption for nearly all developing countries; the total for 1988 for all sectors amounts to 36 EJ, not far below the 47 EJ of commercial energy consumption. Human settlements account for an estimated 80–90% of total biomass use.
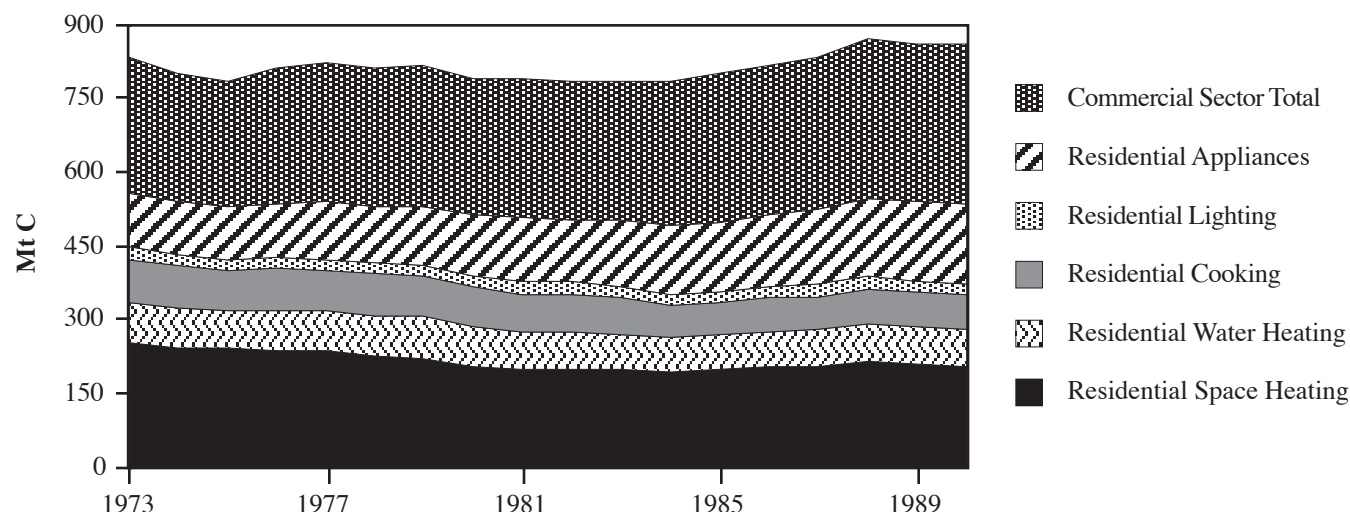
**Figure 22-2:** $CO_2$ emissions from residential and commercial energy consumption in the United States, Japan, former West Germany, France, United Kingdom, Italy, Sweden, Norway, and Denmark (Scheinbaum and Schipper, 1993; Cooper, 1993; Meyers *et al*., 1993b; Meyers, 1994).

since the early 1970s, as rising levels of ownership and increases in the size and features of some appliances have had more impact on energy consumption than have gains in appliance efficiency (Schipper and Hawk, 1991).

The evolution of emissions (or energy use) by end-use for the commercial sector of the industrial countries and for both the residential and commercial sectors of the FSU/EE and the developing countries is less well known. Space heating dominates energy use in both the residential and commercial sectors of the FSU/EE, with an estimated share of around 75% (Cooper and Schipper, 1991). In the developing countries, space heating accounts for only about 20% of total $CO_2$ emissions, with virtually all of that originating in China (Liu, 1993). Emissions associated with energy use by residential appliances and commercial-sector space conditioning have increased in the past decade.

Using the data and estimates described above, we estimate that the residential and commercial sectors accounted for 19% and 10%, respectively, of global $CO_2$ emissions from the use of fossil fuels in 1990 (Figure 22-3).

#### 22.2.2. Non-$CO_2$ Emissions

Regardless of the method of harvest, burning of biofuels (and biomass in general) results in net emissions of methane ($CH_4$), carbon monoxide (CO), nitrous oxide ($N_2O$), and nitrogen oxides ($NO_x$) in addition to $CO_2$. Of these, methane ($CH_4$) is the most significant because of its larger global warming potential (GWP)—which is 24.5 times that of $CO_2$—and the large volume of emission compared to the other gases.[2] The data of Hall (1991) on global biofuels combustion indicate that methane emissions from this source in 1988 amounted to approximately 14 million tons. The GWP is about 100 million tons of carbon-equivalent, which compares to global $CO_2$ emissions from human settlements of approximately 1.7 billion tons carbon (C) (for a 100-year time horizon).

Methane from landfills and from the disposal of domestic and industrial wastewater constitutes the other main source of methane emissions associated with human settlements. Total global methane release from these sources is estimated to be 50 to 80 million tons, as discussed in Section 22.4.4. This amount corresponds to the equivalent of 335 to 535 million tons of carbon-equivalent (using a GWP based on a 100-year time horizon).

### 22.3. Factors Affecting Future Growth of GHG Emissions from Human Settlements

Future levels of GHG emissions from human settlements will be shaped by four basic factors: population, per capita level of energy-using services, energy intensity of the technologies used to provide those services, and energy sources used by those technologies.[3]

#### 22.3.1. Population

Population growth rates depend on a complex mix of cultural, economic, and technological factors, as well as government policies. Declining birth rates are linked to increased economic security, improved health care, and improved opportunities for women, as

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[2] We use a GWP of 24.5 for methane based on the IPCC report *Radiative Forcing of Climate Change*, 1995. The GWP corresponds to a GWP of 1 for $CO_2$ over a 100-year time horizon. In order to convert this into tons of carbon equivalent, the GWP is multiplied by the ratio of the atomic weight of carbon to the molecular weight of $CO_2$. Thus, to convert tons of methane to tons of atmospheric carbon equivalent, we multiply tons of methane by 24.5 x 12/44 = 6.7.

[3] If the energy source is electricity, the level of $CO_2$ emissions also depends on the mix of fuels used for electricity generation and the efficiency of generation and delivery.

well as access to birth-control techniques. The pace of urbanization, which depends in part on the extent of economic development in rural areas, also will affect birth rates. The willingness of countries to adopt and implement policies that limit population growth will play a major role in affecting future population levels.

Projections of population growth vary with the assumptions made about fertility rates and other factors. Recent projections from the World Bank (1993) show an average annual growth between 2000 and 2025 of 0.3% and 0.4% in the OECD and FSU/EE, respectively, but 1.4% in the developing countries. Among the developing countries, projected growth is much slower in China (0.8% per year)—which has and is expected to continue strict population-control policies—than in middle- and low-income countries (1.5% and 1.7%, respectively).

### 22.3.2. Activity Levels in the Residential Sector

The level of energy-using activity in the residential sector depends greatly on income growth and distribution, household size, and the cost of housing and home appliances. The real cost of most appliances has declined over time, which means that households outside the industrialized countries can acquire them at lower income levels than was the case for industrial-country households in the past. Levels of energy-using activity do not expand linearly with income because saturation of major energy-using equipment begins to appear at higher income levels.

#### 22.3.2.1. Industrialized Countries

The number of households is increasing faster than population because of a decline in household size. Decline in household



**Figure 22-3:** Shares of residential and commercial sectors in global $CO_2$ emissions from energy consumption, 1990. Global emissions in 1990 are estimated as 5.75 billion tons of carbon, using the ratio of 1990 to 1985 global commercial energy consumption, and 1985 global $CO_2$ emissions given by the IPCC (1991). See text for sources of residential/commercial $CO_2$ emissions.

size will have the largest impact in Japan, which has much larger households today than the other industrialized countries.

Growth in per capita ownership of major appliances, which pushed household electricity use up considerably in the 1970s, will have a much smaller impact in the future because ownership of refrigerator-freezers, freezers, color televisions, and clothes washers is approaching saturation.
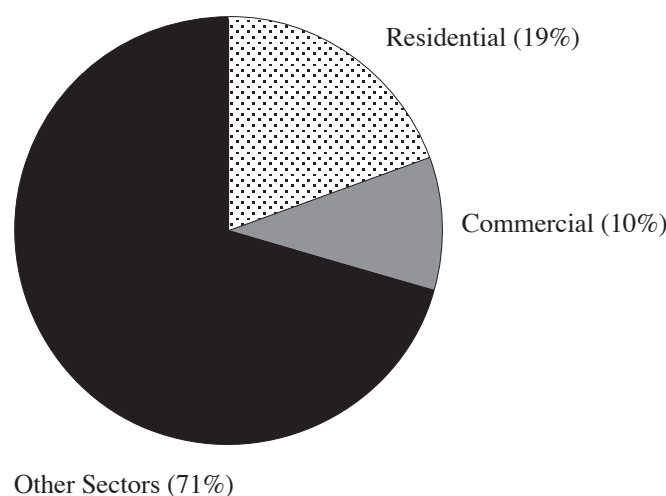
#### 22.3.2.2. Developing Countries

The combination of rising population, urbanization, increases in per capita income, and further spread of electrification in rural areas will lead to tremendous growth in demand for residential energy services in the developing countries. Household size will fall with urbanization and decline in fertility rates, as has already occurred in newly industrialized economies in Asia. As in other parts of the world, this decline in household size will increase per capita energy use.

Changes in equipment and fuels will have a major impact on cooking, currently the most important residential end-use in the developing countries. The transition from biomass fuels to kerosene and liquefied petroleum gas (or electricity in some cases) already has occurred to a large extent in urban Latin American households and is proceeding rapidly in urban Asian households (Sathaye and Tyler, 1991). In much of sub-Saharan Africa, on the other hand, the transition to non-biomass fuels has been slowed because of a decline in incomes and fuel distribution problems. The transition will be much slower among rural households that have greater access to biomass resources as well as lower incomes.

Where electricity is not available, kerosene is generally used for lighting, providing much lower lighting levels and consuming far more energy than does electric lighting (Fitzgerald *et al.*, 1991). Thus, electrification will reduce energy use for lighting; at the same time, it will provide an enormous potential for growth in appliance ownership, especially in Asia and Africa. Market penetration of TV sets already is relatively high among electrified households, but penetration of refrigerators is still low (20 to 25%) even in middle-income countries like Thailand and the Philippines—and is lower still in populous countries such as India, China, and Indonesia (Meyers *et al.*, 1990). Refrigerator ownership will grow rapidly as the economies of these countries expand. The other major appliance whose penetration is likely to grow considerably is the automatic clothes washer.

A key uncertainty is the extent to which air conditioning will grow. Its market penetration currently is very low: 2% of homes in the Philippines, 1% in Thailand, and 4% in Brazil. However, the experience of Taiwan, where the proportion of dwellings with air conditioning rose from 12% to 29% of households in the 1980s, suggests that the use of air conditioning could rise in warm climates as households reach upper middle-income levels.

### 22.3.2.3. *Former Soviet Union/Eastern Europe*

Overall, increased demand for energy services in the residential sector in the FSU/EE will depend critically on how soon the region can reestablish its various economies. Following fundamental restructuring of the economies and economic recovery, the demand for increased energy services will be largely driven by two factors: increasing housing area per capita (which could rise very rapidly under favorable economic conditions) and increasing demand for appliances. Population is growing slowly, but household size (currently between 3 and 3.5 persons) will fall as more housing is built. House area may grow, particularly if private initiatives lead to increased construction of low-rise and detached (or semi-detached) housing. Central heating penetration will increase, particularly outside of large cities with district heat. Ownership of various electric appliances also will grow somewhat, as will their size and features.

### 22.3.3. *Activity Levels in Commercial Buildings*

#### 22.3.3.1. *Industrialized Countries*

Between 1973 and 1988, the service sector grew 1.3 times as fast as total gross domestic product (GDP) in the United States, 1.4 times as fast in Japan, and 1.8 times as fast in the former West Germany. The service sector is expected to continue to grow more rapidly than GDP in the industrialized countries for the foreseeable future.

Expansion of service-sector floor space is likely to be especially strong in health-care (because of aging populations) and leisure-related buildings (because of increased leisure time among workers and growth in the numbers of retired persons). Both of these sectors are relatively energy-intensive.

#### 22.3.3.2. *Developing Countries and Former Soviet Union/Eastern Europe*

Large increases in service-sector floor area will occur in the developing countries. Many types of services that have fed the growth of the commercial sector in industrialized countries are just beginning to expand in many developing countries. Hotels and other facilities for tourists also will grow substantially. In the public sector, growth in population will require a substantial increase in education and health-care buildings.

The FSU/EE region currently has less than 5 m² of service-sector area per capita—about half the level of Italy (Cooper and Schipper, 1991). Office and retail space will increase considerably to meet the demands of the emerging private sector. Growth also will occur in lodging and restaurants.

### 22.4. Potential for Reducing GHG Emissions

### 22.4.1. *Residential Buildings*

The potential for cost-effective improvement in energy efficiency in the residential sector is high in all regions and for all end-uses. Although a large majority of the net global $CO_2$ emissions from the residential sector is from industrialized countries, their share of the technical potential for improvement is somewhat smaller for two reasons. First, considerable improvement in the energy efficiency of existing homes, new homes, and equipment in the industrial countries has already taken place over the past two decades, prompted both by higher energy prices and by policies and programs. Thus, the potential for further cost-effective gains, while still considerable, is less than it was in the past.

Second, growth in both the number of households and in equipment stocks per household is increasing much faster in the developing countries than in the industrialized countries, and the average efficiency of new equipment is lower because of the need to keep initial costs low. Much of the new equipment uses electricity, and a good share of the growth in ownership is occurring in countries whose power supply is likely to be dominated by coal. Thus, there is much potential to affect future $CO_2$ emissions by improving the efficiency of residential buildings and appliances in these countries.

#### 22.4.1.1. *Space Conditioning*

Space conditioning (heating and cooling) accounts for about half of residential $CO_2$ emissions from North America and Europe; the largest portion of this is heating rather than cooling. In contrast, relatively little energy is consumed for space conditioning in developing countries, with the important exception of China. This is due, in part, to the much warmer climate in the majority of developing countries and, in part, to the lower level of economic development. As these countries develop, air conditioning will consume rapidly increasing amounts of energy.

The energy consumed for space conditioning can be reduced through increases in the thermal integrity of buildings (i.e., improvements in walls, roofs, and windows), increases in the efficiency of space-conditioning equipment, and improved controls for such equipment. Other ways to alter buildings to reduce energy use include reductions in leaks in ducts carrying hot or cold air to the conditioned space (of particular importance in North America), design changes (e.g., the use of passive solar design), and environmental changes (e.g., the adoption of increased shading and wind breaks from trees and other vegetation). Finally, behavioral factors, such as the timing and level of indoor-temperature settings, have a great deal of influence on the energy use of residences.

Switching from high-$CO_2$ to low- or no-$CO_2$ energy sources also can reduce $CO_2$ emissions from space heating. In the industrialized countries, a significant shift to natural gas and

nuclear-generated electricity has already occurred during the past 20 years; further movement toward gas is likely in Western Europe. Eastern Europe and China have considerable potential for switching away from inefficient coal stoves to gas or district heating.

### 22.4.1.1.1. Building thermal integrity

Opportunities to enhance the energy efficiency of a building shell occur throughout a building's lifetime. Prior to construction, designs with proper orientation, adequate insulation levels, overhangs, and high-quality windows will reduce energy use. In construction, proper sealing and adequate and well-distributed insulation will reduce losses through building shells. Lastly, retrofits—such as the addition of insulation, and storm doors and windows, as well as reduction of thermal bypasses and air leakage—often can save considerable energy. Reducing infiltration is particularly important in many climates; techniques now exist to do this while minimizing the impact on indoor-air quality. So-called "low-energy" homes have demonstrated the technical feasibility of reducing heating requirements to very low levels through the use of high levels of insulation, passive solar design techniques, and other measures, but these have achieved only limited market penetration to date.

Low-emissivity (or low-e) coatings (clear coatings added to glass surfaces) allow the transmission of solar radiation into the interior but reduce radiative heat losses (Rosenfeld and Price, 1992). The addition of a low-e coating can reduce the heat losses of a double-pane window by about one-third. Low-e windows cost 10 to 20% more than regular windows and therefore are generally cost-effective. A double-pane window with gas-filled spaces and two suspended reflective films inside can reduce heat loses by 75%. Improvements in window frames—e.g., greater use of thermal breaks to limit conduction losses through the frame—offer another opportunity for energy savings.

A study for the former West Germany that evaluated homes of different vintages in five building types found that, on average, investments that save 40% of baseline heating energy would be cost-effective even when future energy prices are low (Ebel *et al*., 1990). A 50% reduction in energy expenditure, however, costs considerably more and would be cost-effective only when energy prices are high.

In the United States, recent studies estimate that energy savings of 30 to 35% could be attained between 1990 and 2010 through retrofits in dwellings built before 1975, but only about half of these retrofits would be cost-effective (EIA, 1990; Koomey *et al*., 1991). The energy-savings potential for dwellings built between 1975 and 1987 is somewhat less than that for those built before 1975. In the United States, an estimated 25% of residential heating and cooling energy use is associated with losses through windows (Bevington and Rosenfeld, 1990). Analysis for the U.S. housing stock suggests that most cost-effective, currently available energy-saving window systems

could reduce energy losses through windows by two-thirds (Frost *et al*., 1993).

Among industrialized countries, Sweden has gone the furthest in institutionalizing high levels of thermal integrity in new homes (Schipper *et al*., 1985). Adoption of Swedish-type practices, which rely heavily on factory-built components, in the rest of Western Europe and North America would probably bring a reduction of at least 25% in the space-heating requirements of new dwellings relative to those built in the late 1980s (Schipper and Meyers, 1992).

Building practices in Eastern Europe have resulted in energy efficiency that is well below Western levels (Cooper and Schipper, 1991; Meyers *et al*., 1993b). Although there are no reliable estimates for the magnitude of energy savings that could be achieved by improving the thermal characteristics of building shells, the potential is likely to be much greater than for Western Europe. Particularly large improvements are possible through reducing air infiltration, increasing roof insulation, and improving the performance of windows. Adequate metering and occupant control systems are needed.

In developing countries where the use of air conditioning is rising, improvements in building thermal integrity can reduce cooling requirements. A study for Thailand found that installing 7.5 cm of insulation in the attic of a typical single-family house would reduce air-conditioning requirements 30% (Parker, 1991). For new homes, building design, reflective materials, and landscaping strategies that minimize solar gains in the summer and enhance natural ventilation can eliminate the need for mechanical cooling even in warm climates and reduce cooling loads in hot, humid climates.

China has a large number of households in regions requiring heating, a large potential for growth in heating demand as restrictions on heating are eased, and heavy reliance on and inefficient use of coal. Considerable potential exists to improve building thermal integrity (especially in new buildings). Since indoor temperatures in most homes are lower than desired, some or even most of the savings from efficiency will go toward greater indoor comfort rather than reduced energy use. Even so, increases in wall and ceiling insulation and in the thermal characteristics of windows can reduce energy use by 40% relative to mid-1980s practice, while allowing a considerable increase in indoor temperatures (Huang, 1989). The government has introduced a standard that calls for new buildings in cities to be designed to use 30% less heating energy relative to 1980 practice, with implementation in the early stages (Siwei and Huang, 1992).

### 22.4.1.1.2. Space-heating equipment and air distribution systems

In 1992, the United States set a minimum efficiency of 78% for new gas-fired, warm-air furnaces. However, units using "condensing" technology, in which the latent heat of water in the

flue gas is recovered, are far more efficient—in the range of 90 to 97%. At present, sales of condensing furnaces are 20 to 25% of total sales, even though their price is considerably higher (typically about $600 more than noncondensing units). The cost-effectiveness of these furnaces depends on the climate and the cost of fuel; measured energy savings from condensing-furnace installations in colder climates in the United States yield simple paybacks of 4 to 7 years (Cohen *et al*., 1991).

Electric air-source heat pumps are about twice as efficient as electric resistance heaters, and technological improvements could increase the coefficient of performance (COP; the heat delivered divided by the energy consumed by the pump) to as high as 5 in moderate climates (Morgan, 1992). Ground-source heat pumps are even more efficient than air-source heat pumps (U.S. EPA, 1993f). Heat pumps are most effective where both heating in winter and cooling in summer are needed.

Recent research has indicated that, for houses in the United States in which hot or cold air from the furnace or air conditioner is carried by ducts in contact with the outside, leaks and thermal losses from the ducts are typically 30 to 40% of the energy carried by the ducts (Modera, 1993). New techniques are under development to treat ductwork in existing and new houses to reduce or eliminate these leaks (Jump and Modera, 1994; Modera *et al*., 1992; Treidler and Modera, 1994; and Proctor *et al*., 1993).

In the FSU/EE, the majority of residential complexes are heated through district heating systems, with or without cogeneration. In addition to significant technical efficiency improvements in these often-antiquated heating systems and better insulation of pipes that carry heat to and among buildings and apartment units, energy savings can be realized through improvement of the operation and control of heating systems. Lack of metering and controls for district heat discourages household conservation efforts. Options include repairing inoperative radiator valves and installing thermostats and individual apartment meters. The latter cannot be easily installed in all buildings, however, because heating systems piped in series (where the output of one radiator is the input to another) require the installation of a bypass pipe. Building heat-distribution systems can be improved through controls that adjust hot-water temperature in response to outdoor temperature, shut off the hot water when no space heating is necessary, or set back temperatures at night (U.S. Congress, OTA, 1993b).

In China, 75% of heated residential space is heated by coal-burning stoves, and 25% is supplied through small boilers or district-heating systems (Liu, 1993). The efficiency of central-heating systems in China often is quite low, and there are many opportunities for cost-effective efficiency improvements (Liu, 1993). Conversion from coal-burning stoves to more modern heating systems appears to increase energy use; however, it does greatly reduce indoor air pollution, provide better control of temperature, and greatly reduce personal effort and inconvenience. Thus, trends to modernize heating in urban areas of China could actually increase carbon emissions as compared with direct coal-burning stoves, but that increase can be moderated by investments in efficient equipment.

### 22.4.1.1.3. Air-conditioning equipment

Efficiency improvements for air conditioners include better internal insulation in the equipment, larger heat exchangers, higher evaporator temperatures, dual-speed or variable-speed compressor motors to reduce on-off cycling, more efficient rotors and compressors, advanced refrigerants, and more sophisticated electronic sensors and controls (Morgan, 1992). A typical central air conditioner in the United States purchased in 1990 was 36% more efficient than a 1976 model (Levine *et al*., 1992). The most efficient models in the market are 40% more efficient than the average new model; 20% efficiency gains over the average new model are cost-effective in many regions of the United States (Levine *et al*., 1992; and Koomey *et al*., 1991).

In the developing countries in particular, considerable improvement in the efficiency of air conditioners is possible through more widespread use of design options that are common in the industrialized countries (Meyers *et al*., 1990). In Thailand, for example, the average home air conditioner draws 1.6 kW, whereas the best units require less than 1 kW to provide the same cooling capacity (Parker, 1991).

### 22.4.1.2. Water Heating

As with space heating, water heating is a major end-use, mainly in North America and Europe. Increased insulation of water heaters, electronic ignition of gas water heaters, and higher efficiency gas burners all promise significant savings over conventional technology. Air-source heat-pump water heaters can provide very high efficiency in warm climates; exhaust-air heat pumps (in which the heat from the exhaust air in ventilation systems is pumped into the stored hot water) are another promising option. Ground-source heat pumps (for space conditioning and heating water) can further increase efficiency and allow application into colder climates. In Eastern Europe, separate provision of domestic hot water from space heating—to reduce the enormous summertime losses in large-scale heat systems that provide only domestic hot water—can contribute energy savings.

Although water heating is not a major end-use in developing countries, it is becoming more common. Options similar to those common in the industrialized countries are available, but increased insulation for storage water heaters yields smaller benefits in warm climates. Solar water heaters are cost-effective in many areas, provided demand for hot water is sufficient, but their high initial cost is a barrier.

### 22.4.1.3. Lighting

In most developing countries, lighting is the most important electric end-use. Expanded use of compact fluorescent lamps

(CFLs), which require 20 to 25% of the electricity of standard incandescent lamps to produce the same light output, could have a major impact there. Studies of the potential for CFLs in India and Brazil have shown that their use would be highly cost-effective from national and utility perspectives (Gadgil and Jannuzzi, 1991). The cost of avoided peak installed electric capacity from the use of CFLs rather than incandescent lamps is as low as 10% and 15% of the cost of new installed capacity for Brazil and India, respectively, but subsidized electricity prices and the high initial cost of CFLs limit their attractiveness to households. The extent to which these lamps spread will depend on programs to overcome the first-cost barrier.

Replacing a kerosene wick lamp with a 16-watt compact fluorescent lamp increases light output 22-fold, while reducing the fuel-use rate by a factor of 8, even taking into account energy losses in generating electricity (van der Plas, 1988). The potential for cost-effective energy savings in electric lamps is especially large for households that do not yet have access to electricity. According to one estimate, some 2.1 billion people (about 35% of the world total) do not have electricity (Efforsat and Farcot, 1994); they consume an estimated 0.29 EJ of kerosene (Dutt and Mills, 1994; Dutt, 1994).

### 22.4.1.4. Cooking

Cooking is a relatively minor end-use in the industrialized countries and Eastern Europe, but it is the largest home energy use in most developing countries. Its predominant role is caused not only by the low saturation of other equipment and the lack of space-heating demand but also by the low conversion efficiency of the biomass stoves upon which most households rely. Traditional stoves are only 12 to 18% efficient.

The impact of the transition from biomass fuels to kerosene and liquid petroleum gas (LPG) on global warming depends on the source of the biofuels (whether harvested sustainably or not), the magnitude of products of incomplete combustion (PIC) from biomass stoves, and the global warming potential (GWP) of PIC, which can be considerable. PIC from biomass stoves include CO, methane, and a range of volatile organics. As a mixture, the total PIC GWP from a typical biofuel stove is usually greater than the GWP of the same amount of carbon as $CO_2$. Exactly how much greater depends on whether indirect as well as direct warming effects are included in the GWP calculations, the time horizon used, and the particular PIC mixture. A kerosene stove produces far less PIC; in addition, much less carbon is involved because a kerosene stove is more efficient and the fuel has more energy per carbon atom than does biomass. In a measured experiment based on cooking the same meal on a kerosene stove and a wood stove, the combined GWP of $CO_2$ (assuming nonsustainable harvest) and PIC (assuming a 20-year time horizon and including indirect warming effects) was about five times greater for a wood stove than for a kerosene stove (Smith *et al.*, 1993). Using a 100-year time horizon would reduce the effects of combusting biomass in a wood stove to about 2.5 times that of a kerosene

stove. These factors are highly uncertain because the GWP of PICs is not known accurately (IPCC, 1994).

Fuel used for cooking a standard meal can be reduced by 30 to 40% through improved wood-burning stoves (Leach and Gowan, 1987; Smith, pers. comm.). An additional 50% fuel savings could be realized by switching to a kerosene stove (Dutt and Ravindranath, 1993). Although producing a significant savings, the switch from wood to kerosene reduces fuel use less than expected because some of the fuel savings is taken back through improved cooking (Fitzgerald *et al.*, 1991). Where fuelwood is gathered and traditional cookstoves are homemade, there are no direct economic benefits to the households of switching to kerosene for cooking. In urban areas, or wherever fuelwood is sold, improved fuelwood stoves as well as kerosene stoves are likely to have far lower life-cycle cost (Dutt and Ravindranath, 1993). The diffusion of improved fuelwood stoves often has failed, however, because they did not fulfill cooking requirements or because of cultural factors, especially in rural areas (Piacquadio Losada, 1994).

Biogas, derived from the anaerobic decomposition of crop wastes and dung, is an alternative cooking fuel, either at the household level or at a community level. The production and use of biogas can result in no net $CO_2$ emissions and overall reduction in methane emissions compared to spontaneous decay. However, production of biogas as a cooking fuel is not economical compared to improved fuelwood or kerosene stoves (Dutt and Ravindranath, 1993).

Ethanol produced from sugar-cane fermentation is an alternative cooking fuel in areas with surplus sugar-cane production. At the lower end of the range of ethanol production costs, around \$7/GJ (Ahmed, 1994), ethanol could be cost-competitive with other cooking alternatives (Dutt and Ravindranath, 1993). There are no net emissions of $CO_2$ from the use of biogas or ethanol.

Solar ovens are used to replace biomass fuels in many developing countries. Use of these ovens reduces the harvesting of carbon-sequestering trees and eliminates GHG emissions from burning wood or substitute fuels, such as kerosene and LPG. Currently, an estimated 100,000 solar ovens are in use in China, and more than 300,000 in India. Other countries with large numbers of solar ovens include Kenya, Costa Rica, Jamaica, Guatemala, Belize, El Salvador, and Honduras.

In the industrialized countries, there is relatively limited potential (10 to 20%) to improve the energy efficiency of primary cooking devices. In these countries, cooking energy use per household is likely to decline somewhat because of the proliferation of small kitchen appliances and changes in cooking habits (e.g., increased use of microwave in place of infrared heating systems).

### 22.4.1.5. Electric Appliances

Because most home appliances have lifetimes of 10 to 20 years, changes in new appliances shape the intensity of the

stock rather quickly. Such changes can be significant in developing countries, where stocks are growing rapidly.

A series of analyses conducted to support setting energy-efficiency standards in the United States established considerable potential for cost-effective efficiency improvement for most major electric appliances (U.S. DOE, 1989a, 1989b, 1990, 1993). For new refrigerators in the United States, the average efficiency (measured in terms of refrigerated volume per unit of electricity consumption) has increased by almost 200% between 1972 and 1994 (Association of Home Appliance Manufacturers, 1995). Energy use has not declined in proportion to the increase in efficiency because of new features such as icemakers and larger model sizes. Standards applied in 1993 reduced electricity use by 28% relative to the average model produced in 1989 (Turiel *et al*., 1991). Advanced compressors, evacuated panel insulation, and other features have the potential to produce commercial and cost-effective refrigerators that consume half as much electricity per unit volume as those that meet the 1993 standard. Such a refrigerator would consume 20% as much electricity as a typical 1972 U.S. model. Recent studies found similar results for European refrigerators and freezers (Lebot *et al*., 1991; GEA, 1993).

For clothes washers and dishwashers, analysis for the United States found that design options that reduce energy use by 30% (including energy to heat water) are cost-effective (EIA, 1990). For clothes washers, a change from vertical-axis to horizontal-axis technology would reduce energy use by about two-thirds relative to the baseline (mainly because of much lower use of hot water). Increasing the spin speed during the spin-dry cycle of a clothes washer can reduce drying energy use by 30 to 50% (because much less energy is expended in mechanical water removal than in thermal water removal). Many European washers are horizontal axis and use higher spin speeds than are standard in the United States. For clothes dryers, the cost-effective reduction in energy use is only 15%, but much greater savings (about 70% relative to the baseline) are possible through the use of a heat-pump dryer. The latter has a significantly higher cost, but a prototype has been developed and successfully tested.

In Eastern Europe, inefficient components are currently being used in most domestic appliances. Refrigeration appliances produced in Poland consume substantially more energy than similar models made in Western Europe (Meyers *et al*., 1993a). Production facilities are in need of substantial modernization to produce higher quality and more-efficient appliances.

In the developing countries, the most important appliance to target for efficiency improvement in the near term is the refrigerator, whose saturation is growing rapidly. In the longer term, air conditioners will be of great importance. The majority of refrigerators and air conditioners sold in the developing world are well below the state of the art, although the lack of test data makes detailed knowledge of efficiency and energy use impossible (Meyers *et al*., 1990). A study that considered a variety of appliances in Indonesia estimated that the use of best-available cost-effective technology would result in a reduction in energy use of 20 to 30% relative to the 1988 stock average (Schipper and Meyers, 1991).

### 22.4.1.6. *The Overall Potential for Residential Energy Savings*

Several studies at the national and regional levels in the industrial countries have developed estimates of future residential energy use if greater use is made of energy-efficient technologies and practices. Estimating cost-effective savings is a difficult task. Technology is just one of many factors affecting energy use, and the effects of technological change may be masked by population increases, demographic shifts, and other factors. Technology is not stagnant; costs, performance, and efficiencies change as technology is improved and refined. The diversity of the building stock, climatic variations, and uncertainty over future energy costs all make estimating the economic potential for energy savings an uncertain exercise. Furthermore, there are several measures of cost-effectiveness, and one can consider different perspectives—such as the consumer, the utility, and society as a whole. Finally, one can vary the values of inputs in economic calculations, notably the discount rate.

Bearing in mind the inevitable uncertainties and effects of the different definitions of "cost-effective," it is nevertheless useful to review estimates of the energy savings that could result from greater use of cost-effective technologies.[4]

One study estimates that, relative to the predicted business-as-usual 2010 consumption, 13% of the energy used in U.S. homes could be saved with cost-effective technologies; 26% could be saved with technically feasible, but not necessarily cost-effective, technologies (EIA, 1990). These estimates are at the low end of the range of cost-effective savings found in other studies, probably partly due to conservative assumptions concerning building shell retrofits.

One assessment of the residential efficiency potential for electrical end-uses in the United States looked in detail at measures for all end-uses and different building types (Koomey *et al*., 1991). The study estimates 40% cost-effective savings for the year 2010, where savings were calculated from a baseline with energy efficiency fixed at today's levels, current energy prices were used, and no new technology was assumed (see Figure 22-4).[5]

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[4] This refers to technologies that save energy at a cost lower than the average cost of energy or the cost of new supply, depending on the measure of cost-effectiveness used. The cost may be calculated using a discount rate of 6–10% real, reflecting the customers' cost of capital in an industrialized country, or 3–4% real if a social discount rate is used.

[5] As noted, the baseline assumes that buildings and appliances existing in 1990 remain at 1990 efficiency levels (no retrofits) and that all new homes and appliances that enter the stock remain at the efficiency of new systems in 1990. Thus, stock turnover reduces average energy intensities in the baseline case even though new and existing devices are frozen at their 1990 efficiencies.
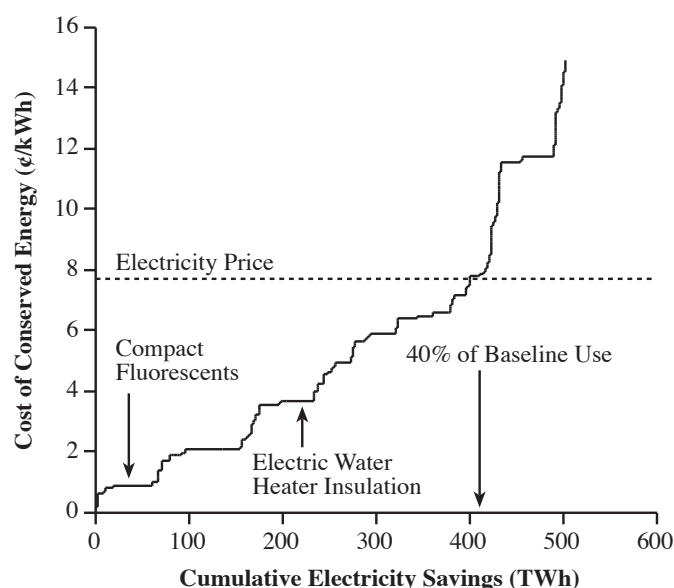
**Figure 22-4:** Conservation supply curve for electricity in the U.S. residential sector (each "step" represents a specific electricity conservation measure).

Studies conducted in Japan have assessed cost-effective energy savings potential in the year 2010 and thereafter (Japanese Environment Agency, 1992; Tsuchiya, 1990). The greatest energy savings for residential buildings would come from reduction of heating demand through greater insulation in the building envelope and double-glazed windows; provision of space heating and cooling, along with hot water, through multifunction heat pumps; and introduction of solar water heaters. Without energy-efficiency improvements, $CO_2$ emissions from residential energy use in Japan are projected to increase to 150% of 1990 levels by 2010; with a strong

effort to implement cost-effective efficiency measures, $CO_2$ emissions are projected to be 107 to 123% of 1990 levels. In the longer term (2020 and beyond)—with more time for turnover of building and equipment stock—energy-efficiency measures are projected to be able to bring $CO_2$ emissions to 97% of 1990 levels.

The energy savings and costs associated with a variety of measures that could be applied for existing and new housing in former West Germany, France, Italy, the United Kingdom, and the Netherlands are evaluated by Krause *et al*. (1994). Cost-effective savings of 40 to 45% in heating requirements are considered possible for gas- or oil-heated residential buildings existing in 1985 that survive to 2020. Cost-effective savings of 28 to 35% are estimated for existing buildings with district heating systems. For residential buildings built between 1985 and 2020, heating energy requirements could be reduced in a cost-effective manner by as much as 70%.

Although the modern sector of developing countries shares many of these opportunities, there is an important difference: The energy consumption in developing countries is much lower but generally has higher rates of growth, because of population increase as well as the increase in energy services per capita. Thus, opportunities are more significant in new buildings and equipment than in retrofits. There also are opportunities unique to developing countries. The overall potential for $CO_2$ emissions reduction through energy-efficiency improvement and fuel switching is illustrated in Table 22-1 for India. Emissions reductions of 40 Mt (35%) from 1987–88 emission levels are projected. By the year 2010, with a 1.46-fold increase in population and a doubling of the per capita demand for energy services, $CO_2$ emissions would scale up to 336 Mt with no mitigation but only to 217 Mt with successful mitigation.

*Table 22-1:* Potential for $CO_2$ emissions reductions in India.

| | $CO_2$ Emissions (Mt) (1987–1988) | Reduction Potential (%) | $CO_2$ Emissions (Mt) with Mitigation (1987–1988) |
|---|---|---|---|
| Biomass Combustion | 47.6 | 35 | 30.9 |
| Kerosene Lamps | 8.0 | 87.5 | 1.0 |
| Incandescent Lamps | 8.4 | 50 | 4.2 |
| Fluorescent Lamps | 5.3 | 25 | 4.0 |
| Fans | 7.9 | 20 | 6.3 |
| Refrigerators | 5.3 | 50 | 2.7 |
| Commercial Light | 11.8 | 25 | 8.9 |
| All Other | 20.6 | 20 | 16.5 |
| **Total** | **114.9** | – | **74.5** |

Notes: Estimates based on background analysis conducted for Govinda Rao, Dutt, and Philips (1991). Some 16% of all biomass fuels used were logs; this is assumed to be nonrenewable harvesting. Kerosene lamps are assumed to be replaced by fluorescent lamps; the $CO_2$ emissions of fluorescent lamps are shown in the kerosene-lamp row. Far larger emissions reductions are technically possible with existing technology (e.g., refrigerator energy use can fall by 80% or more, commercial lighting use could be reduced by over 50%, etc.).

## 22.4.2. Commercial Buildings

The commercial sector is especially diverse, even within a single country, with a wide range of building sizes, growth rates, fuels used, operating hours, functions served within buildings, amenity levels, and climates. Larger commercial buildings differ from residential buildings because they tend to have more complex space-conditioning systems (often with mechanical ventilation systems to maintain indoor air quality) and are usually internal-load dominated—meaning that space-conditioning demands arise largely from activities within the building (e.g., people, lighting, and equipment) rather than from exterior conditions. In industrialized countries, commercial buildings tend to be relatively large (e.g., in the United States, 80% of the commercial floor area is in buildings larger than 1,000 m²) and designed for high amenity levels in terms of thermal and lighting conditions. In developing countries, buildings are smaller, with fewer amenities—though the trend is toward the styles of industrialized countries. Commercial building types include offices, hotels, retail stores, schools, health-care facilities, food-service and sales buildings, warehouses, theaters, museums, and religious buildings. The commercial sector includes buildings in both the public and private sectors.

Electricity is the major form of energy consumed in commercial buildings worldwide, dominating all end-uses except space and water heating and cooking. In the U.S. and OECD commercial sector, electricity meets about 70% of demand in terms of resource energy (EIA, 1994). Within the OECD, the share of electricity (on a resource energy basis) in the commercial-sector fuel-mix ranges from a low of 40% in hospitals in Japan to a high of 80% in hotels and restaurants in Norway.

The major commercial sector end-uses include lighting, space heating, space cooling, ventilation, service water heating, office equipment and other plug loads, refrigeration, and cooking. Data on national average end-use shares of energy in commercial buildings are rare. For the United States, Figure 22-5 shows the end-use breakdown for resource energy (Belzer *et al*., 1993). In developing countries, the end-use shares for energy differ considerably from those in industrialized countries. For example, lighting is estimated to account for 50% of total electricity in Indian commercial buildings, with space conditioning and refrigeration accounting for 40% and other end-uses the remaining 10% (Nadel *et al*., 1991).

### 22.4.2.1. Space Conditioning

#### 22.4.2.1.1. Building thermal integrity

Although larger commercial buildings tend to be internal load-dominated, important savings opportunities nonetheless exist in the design of the building envelope. Windows often represent the largest pathway for heat gain and loss through both conductive and radiative heat transfer. Strategies for reducing energy use associated with windows include: reducing window
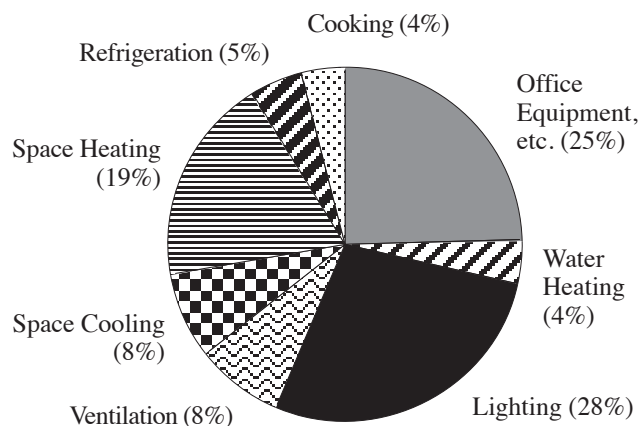


**Figure 22-5:** Shares of U.S. commercial resource energy by end-use, 1989.

area, installing external and internal window shading devices, using multiple-pane windows, injecting rare-earth gases between window panes, and applying low-emittance coatings to window glazing surfaces (Sullivan *et al*., 1992). Low-emittance windows can reduce thermal heat transfer while still transmitting visible light into the interior space, making this technology particularly effective in daylighting applications.

Heat loss and gain through opaque walls and roofs can be reduced by adding insulation and using high solar-reflectance materials for exterior surfaces, though the effectiveness of these measures diminishes for larger buildings with small surface-to-volume ratios.

Shading low-rise commercial buildings by planting trees for sun and wind protection can reduce cooling and heating loads, respectively (Akbari *et al*., 1992). Through careful window sizing and placement, interior design, and building siting, natural ventilation can be used in some circumstances to augment or supplant the need for mechanical cooling (e.g., Bauman *et al*., 1992; Boon-Long *et al*., 1992).

#### 22.4.2.1.2. Space-heating equipment and air distribution systems

Systems for heating, ventilating, and air conditioning (HVAC) account for 40 to 50% of electricity use in commercial buildings in some industrialized countries, such as the United States and Germany (IEA, 1989). In other industrialized countries, such as Japan, and in many developing countries, HVAC represents less than 25% of electricity use in commercial buildings.

For commercial buildings, there have been moderate improvements in the efficiency of larger air-conditioning systems during the past decade or so. Levine *et al*. (1992) estimate the potential for cost-effective efficiency improvements in chillers in the United States to be 25 to 38% with currently available technology. Advanced technology—more efficient condensers and improved heat exchangers, wider applicability of large

water-cooled chillers, development and application of evaporative cooling techniques, and application of gas-driven chillers—has the potential to increase energy-savings opportunities over the next decades.

For space heating, the typical electric system is either electric-resistance or heat-pump technology, the latter being far more efficient though less common. The typical gas or oil system is either an atmospherically vented furnace or boiler. Improvements in heat exchange to extract the heat of condensation from flue gases, power-venting, and pulsed-combustion technology increase gas-furnace efficiency from a typical 50 to 60% to upward of 90% (Krauss, 1992).

District heating involves the production of heat in a central plant, which is then distributed in the form of steam or hot water to many buildings via underground pipes. Such systems are common in Europe. In Denmark, for instance, district heating is used to meet almost half of the space-heating needs in buildings (U.S. Congress, OTA, 1993b). The efficiency of district heating depends on the system used to produce and distribute the heat. When collected as waste heat from some industrial process or in a cogeneration application, overall efficiency can be very high relative to more traditional on-site space-heating methods.

Energy for air and water transport within buildings can be reduced by employing efficient motors and impeller designs, by good duct and pipe design to reduce static pressure, and by allowing fans and pumps to operate at speeds that closely match thermal loads. With this last approach, a variable-air-volume (VAV) HVAC system with variable-speed drives on the fans is a significant efficiency improvement over constant-volume systems. The savings from VAV range from 30 to 80% (Usibelli *et al.*, 1985). The efficiency advantages of the VAV system have been so well recognized in the United States that more than three-quarters of central systems installed in new buildings are now VAV (Pietsch, 1992). VAV systems are still uncommon in most regions of the developing world.

Greatly increased use of economizers, heat exchangers, and control systems can yield very significant energy savings. Economizers switch the system to the use of outside air when the outdoor temperature is low enough to cool the building. Heat exchangers reclaim heat from exhaust air from space heating, from waste heat in hot-water circulation, or from the ground. Control systems vary from simple zone temperature control with thermostats to comprehensive energy-management control systems that control a variety of systems in the building in addition to HVAC.

### 22.4.2.2. Water Heating

For many old water-heating systems, combined hot water and space-heating systems are typically highly inefficient. Replacement by stand-alone systems can save 65% (Nadel *et al.*, 1993). The same technologies for improving gas-fired

boilers for space heating are applicable for water heating. Electric heat-pump water heaters also are an option for commercial water heating applications, where COPs as high as 5 are available (Abrams, 1992). The heat rejected from food-storage or air-conditioning systems can, under the proper circumstances, be cost-effectively reclaimed for water heating.

### 22.4.2.3. Lighting

Commercial lighting is provided by three types of systems: incandescent, fluorescent, and high-intensity discharge (HID). As with residential applications, replacing incandescent lamps with CFLs in commercial buildings is a viable savings option and, because of higher usage, can be even more economically attractive in commercial applications.

Fluorescent lighting systems are the most common type of lighting in commercial buildings. Data from OECD countries show fluorescent system market shares for lighting in commercial buildings ranging from 59% in Italy to 90% in Norway (IEA, 1991). In the U.S. commercial sector, fluorescent lamps are in use in 76% of the floor area; incandescent and HID lamps are in use in 19% and 6% of the floor area, respectively (EIA, 1992a). In India, the share of fluorescent lighting is estimated to be around 80% (Nadel *et al.*, 1991).

Five technical options are available to improve fluorescent lamp efficiency: higher surface-area-to-volume ratio, reduced wattage, increased surface area, better phosphors, and reflector lamps (Mills and Piette, 1993).

A lamp ballast is needed to provide a suitable starting voltage, thereafter limiting current flow during operation of fluorescent (and mercury-vapor) lamps. Ordinary magnetic ballasts dissipate about 20% of the total power entering a fixture (Geller and Miller, 1988). In some developing countries, poor-quality ballasts may dissipate as much as 30% (Turiel *et al.*, 1990). More efficient electromagnetic ballasts (also known as core/coil ballasts) make use of better materials to reduce ballast losses to about 10%. Solid-state electronic ballasts cut ballast losses even further and also increase lamp efficacy (lumens of light output per watt of power input) because of high-frequency operation. Such ballasts increase the efficiency of the ballast/lamp system by approximately 20 to 25% relative to that of a system with an ordinary ballast (Verderber, 1988).

Lighting-fixture efficiencies vary from less than 40% to about 92% (Mills and Piette, 1993). Specular reflective surfaces inside a fluorescent lamp fixture can increase the amount of light emitted from a fixture, thereby permitting the removal of lamps (delamping) in retrofit applications or permitting fixtures with fewer lamps to be used in new applications.

HID lamps are used primarily for industrial and outdoor lighting, where very high lighting intensity is required. There are five main types of HID lamps (with efficacy provided in lumens per watt): self-ballasted mercury vapor (20), externally ballasted

mercury vapor (38.5), metal halide (54.2), high-pressure sodium (82.5), and low-pressure sodium (136.4) (Levine *et al.*, 1992). Generally, the most common upgrade is to replace mercury-vapor lamps with high-pressure sodium lamps, for which the lighting quality is little changed.

A number of energy-saving lighting controls are now on the market, including multilevel switches, timers, photocell controls, occupancy sensors, and daylight dimming systems. In addition, "task lights" (small lights that illuminate only the work surface) can reduce general lighting needs. These measures typically result in savings of 10 to 15% for photocell controls, 15 to 30% for occupancy sensors, and up to 50% in perimeter zones for daylighting systems (Mills and Piette, 1993; Eley Associates, 1990; and Rubenstein and Verderber, 1990).

Studies of cost-effective energy savings for lighting in commercial buildings in different countries have produced a range of savings estimates: 35% for the United States (Atkinson *et al.*, 1992); between 36 and 86% for five countries in Western Europe (Nilsson and Aronsson, 1993); 70% in Thailand (Busch *et al.*, 1993); 22% in Brazil (Jannuzzi *et al.*, 1991); and 35% in India (Nadel *et al.*, 1991). All of these studies show substantial savings opportunities; results differ in many cases because of differing assumptions.

### 22.4.2.4.  Office Equipment

Office equipment accounts for one of the fastest-growing end-uses for energy in commercial buildings. This equipment includes computers, monitors, printers, photocopiers, facsimile machines, typewriters, telecommunications equipment, automatic teller machines, cash registers, medical electronics, and other miscellaneous plug loads. Much of this equipment is left on when not in use during the day, overnight, and on weekends, often consuming energy at close to full load. Laptop computers, which rely on battery power, use special low-power microprocessors and have technology built into the microprocessor that automatically switches it to a low-power mode when not in use, returning quickly to full capability when needed. Recognizing this, the U.S. Environmental Protection Agency (EPA) instituted the "Energy Star" program to promote efficiency improvements first in computers but eventually to include other office electronics. For instance, personal computers with the capability of switching to a low-power mode of 30 watts or less (about 75% less than current models) qualify for the EPA logo that identifies high-efficiency equipment (U.S. Congress, OTA, 1993a). A recent analysis of the impact of changes in the energy efficiency of office equipment in New York state found that today's Energy Star equipment could reduce office equipment energy use by 30% by the year 2000 and by 43% by 2010 (Piette *et al.*, 1995).

### 22.4.2.5.   The Overall Potential for Commercial Energy Savings

A number of efforts have been undertaken to combine detailed information about individual technologies for energy saving,

as described above, with economic data and information about the existing building stock and planned additions to estimate overall energy-savings potential in commercial buildings in various countries. The analyses have many complexities and uncertainties, including:

- The wide variety of building types among commercial buildings and the difficulty of generalizing to the whole sector
- Differences in opportunities for energy efficiency between new and existing buildings
- Interactions among multiple energy-conservation measures
- Comprehensiveness of the study and criteria used to select measures
- Economic criteria for cost-effectiveness.

As Figure 22-6 shows, a commercial-sector electricity conservation study conducted for the state of New York found economic electricity-savings potential in the commercial sector to be 47% of present consumption from the societal perspective (Miller *et al.*, 1989). At the national level, the Electric Power Research Institute (EPRI) projected from 22 to 49% maximum technical potential for commercial electricity savings (Faruqui *et al.*, 1990). Also at the national level, Rosenfeld *et al.* (1993) found an economic potential of 55% of present electricity consumption in the commercial sector. These savings are for a future year (typically 2020), and they represent savings from current levels of energy efficiency. They are, however, based on current technology and costs, so additional potential savings will be possible over time if energy prices rise in real terms and new energy-efficiency technologies become available.

Such energy-conservation supply-curve studies are much more rare for natural-gas use in commercial buildings; a compilation of assessments by U.S. gas utilities found between 8 and 24% economic potential in their service territories (Goldman *et al.*, 1993).
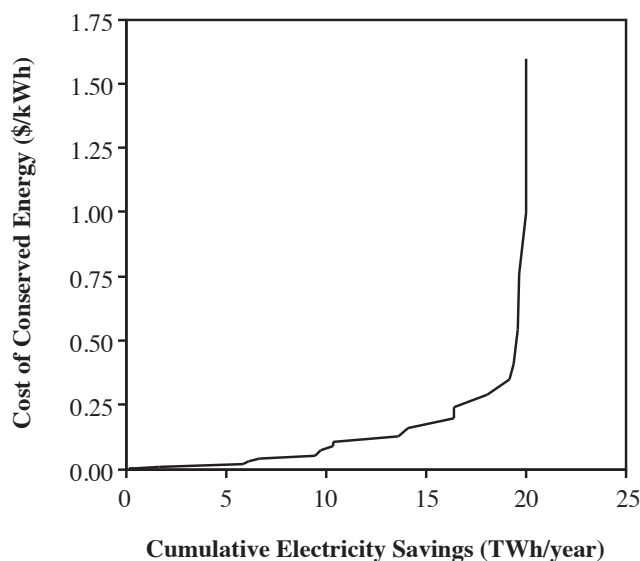
**Figure 22-6:** Conservation supply curve for electricity in New York state's commercial sector.

In Canada, the economic savings potential for all energy used in offices and retail outlets was estimated at 40 and 28%, respectively (Peat, Marwick, Stevenson, & Kellogg, 1991).

An assessment of energy savings potential for commercial buildings in Japan concluded that energy-efficiency measures, primarily for space conditioning and lighting, could reduce emissions of $CO_2$ in 2010 from 125% of 1990 levels (without efficiency gains) to 112% of these levels (Japanese Environment Agency, 1992; Tsuchiya, 1990). The longer term potential was about 70% of 1990 levels.

A recent analysis of the Swedish commercial sector found that total electricity use could remain constant through 2010, despite 45% growth in energy services, through implementation of cost-effective retrofit and new construction measures combined with various government and utility incentive programs (Swisher *et al.*, 1994). A Danish project found a large number of electricity-saving measures in commercial buildings (Gjelstrup *et al.*, 1989). One study, which considered lighting, ventilation, pumping, cooling, refrigeration, and other technologies, found that 24% of public-sector (schools, hospitals, etc.) electricity could be saved by behavior and management changes, and an additional 18% reduction was possible with available technologies (Johansson and Pedersen, 1988). Most or all of these savings were thought to be cost-effective. A study of the private service sector found a somewhat lower conservation potential: 10 to 18% through behavior and management changes and an additional 15% reduction through retrofit (Nielsen, 1987).

Among developing countries, a study of economic electricity-savings potential in Brazil estimated 25% cost-effective savings potential in the commercial sector over the next 20 to 30 years (Geller, 1991). In Thailand's large building sector, a comprehensive analysis of efficiency measures in offices, hotels, and retail buildings calculated savings from 45 to 56% (Busch, 1990). Across Southeast Asia, more than 200 audits of existing commercial buildings have indicated average savings from proposed energy-conservation measures between 10 and 20% (Loewen, 1992).

### 22.4.3. Community-Level Measures: Reducing Urban Heat Islands

The urbanization of the natural landscape—roads, parking lots, bridges, dams, houses, and high-rises—has dramatically altered waters, soils, and vegetation. Replacing vegetation and soil with concrete and asphalt reduces the landscape's ability to lower daytime temperatures through evapotranspiration and eliminates the benefits of shade. The use of dark-colored materials on roads, buildings, and other surfaces creates entire cities that absorb, rather than reflect, incoming solar energy. The combination of reduced reflectivity (called "albedo") and reduced vegetation has resulted in a temperature difference between urban and rural areas that is greatest in late afternoon and early evening, when roads, sidewalks, and walls begin to release the heat they have stored throughout the day.

Throughout the past century, increasing rates of urbanization and industrialization have exacerbated the heat-island effect. Summer temperatures in urban areas are now typically 1 to 3°C higher than in their rural surroundings. Peak temperatures in Los Angeles, for instance, have risen by 3°C in the past 50 years, and mean summertime temperatures in Washington, D.C., have climbed 2°C during the past 80 years. Today, tropical cities are often markedly warmer than their surroundings. Winter nighttime heat islands of 9°C in Mexico City and 6°C in Bombay and Poona, India have been measured (Jauregui, 1984). A comprehensive summary of the heat-island effect in U.S., European, and East Asian cities is provided in Yoshimo (1975, 1991) and Oke (1978).

Heat islands can have either beneficial or detrimental impacts on energy use, depending on geography, climate, and other factors. In warm to hot climates, however, heat islands exacerbate cooling energy use in the summer. For U.S. cities with populations larger than 100,000, electricity use for cooling will increase 10 to 15% for every 1°C increase in temperature (Akbari *et al.*, 1992).[6]

Because urban temperatures during summer afternoons have increased by 1 to 2°C in the past 4 decades, 10 to 20% of the current urban electricity for the cooling of buildings is used to compensate for the heat-island effect alone. Expanded urbanization throughout the world will lead to increasing effects of urban heat islands in the coming decades.

In addition to increasing cooling energy use, heat islands and long-term urban warming affect the concentration and distribution of urban pollution because heat accelerates the chemical reactions that lead to high ozone concentrations [see Akbari *et al.* (1990) for an assessment of effects on ozone levels in Los Angeles].

#### 22.4.3.1. Heat-Island Mitigation

Two factors contributing to urban heat islands can be altered: the amount of vegetation and the solar reflectance of surfaces.

#### 22.4.3.1.1. Vegetation

Trees affect urban climates and building energy use through shading, lowering of windspeeds, and evapotranspiration.

The cooling energy use of two similar sites in Sacramento, California—one with and one without shade trees—was monitored; the shaded site consumed 30% less energy (Akbari *et al.*, 1993). Actual savings at any particular site will depend on

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[6] In a typical city in the United States, cooling accounts for 40% of urban electricity use. Thus, total use is increased (reduced) by 4.5 to 6% for every 1°C increase (reduction) in temperature. Peak demand is typically increased (reduced) by about 60% of this amount.

the nature of the shade trees and the climate. In addition, a tree can transpire up to 380 liters of water a day. In a hot, dry location, this produces a cooling effect similar to that of five average air conditioners running for 20 hours (Akbari *et al*., 1986). In a hot, humid location, however, evapotranspiration is not an effective cooling process.

Considerably greater effects on cooling can be achieved through large-scale tree-planting programs that exert an indirect effect on the community through increased evapotranspiration. Evapotranspiration and shading effects together can reduce air temperatures by as much as 8°C. In Nanjing, China, for instance, after 34 million trees were planted in the late 1940s, average summer temperatures dropped almost 3°C (Garbesi *et al*., 1989).

### 22.4.3.1.2. Solar reflectance of surfaces

The practice of using high solar-reflectance surfaces to keep buildings and outdoor urban areas cool is not new. In many tropical and Mediterranean countries, particularly those with large amounts of sunshine, the traditional architecture has numerous examples of light-colored walls, roofs, and streets. However, in the many industrialized countries—and increasingly throughout the world—architects and urban planners have overlooked this energy-conscious design principle, relying instead on mechanical air conditioning to maintain comfort during the summer months.

Changing the albedo of a building can reduce direct cooling requirements for houses, single-story industrial buildings, and small commercial buildings significantly. For example, 20% reductions in cooling energy requirements have been estimated for a single-story house (Taha *et al*., 1988). Measurements made on a sunny day in November in Berkeley, California, showed that the noontime temperature of a dull black surface was 63°C, whereas that of a white acrylic paint surface was only 25°C (Rosenfeld *et al*., 1994). Similar results would be expected in any location on a hot, sunny day.

Indirect effects (those resulting from the generally lowered temperatures produced by wide-scale increases in albedo) appear to have a larger effect than direct ones. A major program for modifying albedo could reduce urban temperatures by 2 to 3°C, resulting in an estimated reduction of total urban electricity requirements of 8 to 17% and total urban cooling requirements of 21 to 42% (Taha *et al*., 1988).

### 22.4.3.2. Costs and Benefits of Urban Heat-Island Mitigation

Through direct shading and evapotranspiration, trees reduce summer cooling energy use in buildings at only about 1% of the capital cost of avoided power plants plus air-conditioning equipment (Akbari *et al*., 1988). Water consumption and tree-maintenance costs are typically a very small fraction of the costs of avoided electricity, except in hot and very dry climates

where water is scarce (Akbari *et al*., 1992). In the latter climates, most of the savings can be achieved through increased albedo combined with drought-resistant vegetation. Increasing the albedo of a city may be very inexpensive if the change is made at the time of routine maintenance. Buildings are typically repainted every 10 years, and high solar-reflectance paint may be used for no additional cost. Similarly, many roof types, including single-ply membrane and built-up roofing, are available in high solar-reflectance materials for no additional cost.

It has been estimated that a nationwide program of planting urban shade trees and lightening surfaces in the United States could, by the year 2015, reduce cooling energy use by 20%. This annual savings of 108 TWh, worth $7 billion (in 1990 dollars), would prevent the emission of 27 Mt of carbon.[7] (For comparison, the recent Climate Change Action Plan for the United States calls for a carbon reduction of 108 Mt by the year 2000.) Applying similar measures to urban areas in wealthy countries in the rest of the world could approximately double these savings to 50 Mt of carbon by 2015 or 2020. As in the United States, such savings would require very aggressive programs for 20 years or longer.

### 22.4.4. Methane Emissions from Waste Disposal and Wastewater

### 22.4.4.1. Magnitude of Emissions

The anaerobic decomposition of wastes disposed of in landfills or open dumps is a major global source of methane. Recent estimates suggest that 20 to 40 million tons of methane, or about 10% of global methane emissions from human-related activities, are emitted from this source annually (U.S. EPA, 1993a).[8] The large uncertainties in these estimates derive from a lack of information about the amount of organic material actually disposed of in landfills or open dumps by different countries, waste-management practices employed, the portion of organic wastes that decompose anaerobically, and the extent to which these wastes will ultimately decompose (Bingemer and Crutzen, 1987; Orlich, 1990; RIVM, 1993; OECD, 1991; U.S. EPA, 1993a).

Methane emissions result largely from urban areas throughout the world. The industrialized countries of the world contribute about two-thirds of these methane emissions, EE/FSU about 15%, and developing countries about 20% (U.S. EPA, 1993a). Ten countries represent about 60 to 70% of global methane emissions from solid-waste disposal—with the United States

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[7]  The analysis assumes that 40% of buildings are eligible for increased vegetation and reflectivity. The potential savings from direct effects is about 11%. The indirect effect is based on a 2.2°C citywide cooling and is estimated to be about 12%. The combined direct and indirect effects are then about 20% (Rosenfeld, 1994).

[8]  Methane emissions of 20 to 40 million tons per year are equivalent to about 135 to 275 million tons of carbon per year using a GWP of 24.5 for methane, as discussed in Section 22.2.2.

representing about 33%, or around 10 million tons (U.S. EPA, 1993b). With continuing trends in population growth and urbanization, developing countries could account for 30 to 40% of methane emissions from this source by 2000 (U.S. EPA, 1993c).

Methane emissions also result from domestic and industrial wastewater disposal. Recent estimates suggest that 30 to 40 million tons of methane (200 to 275 million tons of carbon in $CO_2$) are emitted annually from wastewater disposal, primarily from the disposal of industrial wastes (RIVM, 1993; U.S. EPA, 1993a). Regional contributions have not been estimated because of the lack of data.

### 22.4.4.2. Reducing Methane Emissions

With available technologies and practices, methane emissions may be reduced either by recovering and using the gas or by reducing the source of methane (U.S. EPA, 1993d). The former approach is most suitable for existing solid-waste disposal sites, which often emit methane (often called landfill gas) for 10 to 30 years or more (RIVM, 1993). Frequently, more than 50% of the generated methane can be recovered (Bhide *et al.*, 1990). In many cases, the recovered methane can be used for heating or electricity generation, which is already common in many countries. Although more expensive, landfill gas also can be purified and injected into a natural-gas pipeline or distribution system; there are several such projects in the United States. In Brazil, purified landfill gas has been used as a fuel to power a fleet of garbage trucks and taxicabs. High-rate anaerobic processes for the treatment of liquid effluents with high organic content (sewage, food-processing wastes, etc.) can help reduce uncontrolled methane emissions and are particularly suited to the warmer climates of most developing countries (Lettinga and van Haandel, 1993).

Options for reducing the source of methane emissions include recycling paper products, composting, and incineration (U.S. EPA, 1993d). Paper products make up a significant part of solid waste in industrialized countries (e.g., 40% in the United States) and a growing proportion in some urban centers of developing countries (typically 5 to 20%) (U.S. AID, 1988; Volger, 1984). A variety of recycling processes, differing in technical complexity, can turn this waste into material indistinguishable from virgin products. Composting—an aerobic process for treating moist organic wastes that generates little or no methane—is most applicable in developing countries, where this type of waste makes up a larger fraction of the total; the residue has fertilizer value. As land-disposal costs rise, incineration (often combined with combustion-energy recovery) has become more cost-effective, especially in lower moisture landfills found in industrialized countries.

Existing methane-recovery and source-reduction projects represent a small portion of the potential. Recent studies suggest that global methane emissions from solid-waste disposal can be reduced by about 30% through the widespread use of existing technologies and practices, making both economic and environmental sense (Richards, 1989; U.S. EPA, 1993c, 1993e). A large part of these reductions could take place in the United States, where a pending landfill rule is expected to reduce emissions nationwide by about 6 million tons, or 60%, by the year 2000.[9] Methane recovery is more economical at large waste-disposal sites located close to large urban areas. Fortunately, such sites represent the majority of methane emissions in many countries.

## 22.5.   Policy Options

### 22.5.1. Buildings

Greater use of available, cost-effective technologies to increase energy efficiency in buildings could lead to sharp reductions in emissions of $CO_2$ and other gases contributing to climate change. However, policies to promote these technologies often are needed.[10] Consumers and other decision-makers often do not invest in efficiency, even though it appears to offer life-cycle cost savings, for several reasons, including:

* Many buildings are rented, causing a separation between those purchasing energy-using equipment and those paying to operate the equipment.
* Individuals pursue several goals when making energy-related decisions (such as minimizing capital outlays), but very few pursue the goal of minimizing life-cycle or societal costs (see Komor and Wiggins, 1988).
* In new construction, where the greatest and most cost-effective savings are available, the builder does not have to face paying energy bills and often works to minimize initial cost.
* Energy costs are relatively low (e.g., about 1% of salary costs in a typical office in industrialized countries), so those concerned with cost reduction often focus their attention elsewhere.

Analysis of U.S. energy-efficiency choices in the residential sector suggests that markets often behave as if consumers had a discount rate of 50% or more (Ruderman *et al*., 1987; U.S. Congress, OTA, 1992b). Discount rates implicit in purchasing decisions involving tradeoffs between capital and operating expenses can be 150% or higher among the poorest Indian households.

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[9]  The landfill rule is designed to reduce emissions of nonmethane organic compounds and air toxics to reduce their adverse air-quality and human-health impacts. It will reduce methane as a side benefit. Greater reductions in methane are expected from this rule than would result if only projects for which reductions in methane releases to the environment were economically viable were undertaken.

[10] For a recent extensive discussion of market failures and energy-efficiency policy issues for the United States, see Levine *et al*. (1994). For a discussion of similar issues related to energy markets in developing countries, see Reddy (1991).

The existence of numerous untapped opportunities for energy savings throughout the world suggests that current market conditions alone will not ensure full implementation of these opportunities. Moreover, energy production and use has significant environmental impacts and other externalities—effects not captured in price.

Yet enthusiasm for policy change must be tempered with a recognition that attempts to increase energy efficiency through regulation or other governmental action may have unanticipated administrative or other costs. Also, current levels of energy efficiency reflect consumer preferences given existing economic incentives, levels of information, and conditions in the market. Finally, there is little consensus on the best policies to promote energy efficiency.

In recent years, many countries have experimented with policies to promote energy efficiency, and evaluation of these efforts has yielded a rich history that can guide future policy efforts. This section describes and summarizes experiences with a range of policy options, including financial incentives, such as energy taxes and rebates; regulations, such as codes and standards; changes in utility regulation; research and development; and improved consumer information.

### 22.5.1.1. Financial Incentives

A basic policy strategy to motivate greater energy efficiency is to decrease the expense and/or increase the financial benefits of saving energy. Specific options include energy price reform and energy taxes, grants and low-interest loans for building retrofits, rebates for the purchase of energy-efficient appliances, tax credits for energy-efficiency investments, and inclusion of energy efficiency in innovative loans and mortgages.

Energy, especially electricity, is often underpriced; its true costs to society are higher than the price paid by consumers. For example, a World Bank review of energy-pricing policies in the developing world found the average market price of electricity was 4.3¢/kWh, whereas the average cost of new supply was 8.0¢/kWh (Mashayeki, 1990).

Reasons for this often glaring discrepancy between market (consumer) prices and true costs include the following:

- Government agencies set prices in response to multiple goals (provision of basic energy services regardless of ability to pay, promotion of specific policies like industrial development, etc.).
- The marginal cost of electricity varies with system load, and marginal cost pricing is technically difficult.
- There is little agreement on the environmental costs of energy production, distribution, and consumption (EPRI, 1991).

Despite these factors, some countries are attempting to move energy prices to include social costs. In the United States, for example, some utilities are incorporating environmental damage costs, including those caused by $CO_2$, into planning decisions (CECA, 1993). Many Central and Eastern European countries, in transition from centrally planned to market-driven economies, are instituting large energy price increases in an attempt to close the gap between societal and market prices. Several European countries are considering or implementing carbon taxes on fossil fuels (CECA, 1993).

There also are circumstances in which electricity prices are far above private marginal cost. For example, advanced turbines using natural gas can produce electricity at costs considerably lower than current costs in most utilities in the United States. This has led to a push for major restructuring of the industry in the United States.

Several key points about energy taxes are worthy of note:

- Energy taxes can raise a tremendous amount of revenue, often at relatively low administrative costs. For example, a 0.1 cent (1 mill) per kWh tax on electricity used in buildings in the United States would raise about $1.7 billion annually (EIA, 1993).
- There is only moderate agreement on the effects of price changes on energy consumption or behavior. Estimates of the price elasticity of energy demand (defined as the percent change in energy consumption resulting from a 1% change in price) range from -0.3 to -1.0 for the buildings sector (Energy Modeling Forum, 1981).
- Taxes may have undesired distributional effects. For example, in the United States, low-income households spend a larger fraction of their income on energy services than do higher income households. Therefore, an energy tax would be regressive (USDOC, 1993). Energy taxes also can be an instrument of income redistribution. Many countries tax gasoline and use a part of the revenues for social expenditures, such as universal health care and education. For example, a small tax on urban electricity consumption in Argentina is used to finance the expansion of rural electrification.

Financial incentives to increase energy efficiency—including grants and low-interest loans for building retrofits, rebates for the purchase of energy-efficient equipment, and tax credits for efficiency investments—account for the majority of public-sector expenditures on energy efficiency in many countries. For example, 84% of the U.S. Department of Energy (DOE) budget devoted exclusively to buildings energy conservation (including research and development) is in the form of grants for retrofits to existing buildings; these grants totaled $230 million in 1991 (U.S. Congress, OTA, 1992a). Similarly, electric and gas utilities are spending an increasing fraction of their demand-side budgets on rebates and direct-payment programs.

Several countries have used innovative technology-procurement programs to promote the development and adoption of

energy-efficient technologies. This approach is known as market transformation because its intent is to transform the market from one using standard-efficiency technologies to one using highly efficient ones. For example, the Swedish government offered a prize for the development of a window with energy losses half that of a conventional triple-glazed window. To ensure marketability, the contest also required maximum visible light transmission, low weight, and low noise transmission. The window that was developed has a typical payback of about 3 to 4 years compared to a double-pane window and 6 to 8 years compared to a triple-glazed window. The winning company received a cash prize, and additional financial incentives of guaranteed first orders for the new model were offered to promote market penetration of the winning design. The United States used a similar approach to promote the development and commercialization of a highly energy-efficient refrigerator.

Financial incentive programs have achieved mixed results. Some programs, such as direct payments to manufacturers for the production of highly efficient products, appear to be quite successful (Lee and Bennett, 1992). Others, such as tax credits, appear to have limited success (U.S. Congress, OTA, 1992a). Program success appears to be tied to the visibility and timeliness of the incentive. For example, a direct cash payment for the desired behavior (e.g., purchase of a highly efficient appliance) often is more effective than a credit for future energy or tax liability, which can be seen as uncertain and less tangible.

### 22.5.1.2. Building Codes

An increasing number of countries are requiring minimum levels of energy efficiency in new construction. As of 1992, at least 30 countries had some type of building energy code (Janda and Busch, 1992). These codes range from voluntary goals for certain types of buildings to comprehensive requirements covering all aspects of building energy use.

A recent field study found that about half of the new commercial buildings in the United States have significant energy-code violations, such as incorrectly sized HVAC systems (Baylon, 1992). This results largely from code complexity and the resulting poor understanding of code requirements by designers, contractors, and regulators. New code requirements must be accompanied by training and education, or compliance will suffer. There is some evidence that simpler building codes do receive greater compliance [e.g., the New Zealand code (Isaacs and Trethowen, 1985)].

The actual savings achieved as a result of energy codes depends on the reliability and effectiveness of technologies employed, the level of code compliance, and the manner in which a building is operated after it is occupied. Building commissioning (inspecting energy-using systems and measuring energy use after construction) is one way to help ensure that actual building energy use meets design goals.

### 22.5.1.3. Appliance Standards

A small but growing number of countries require minimum energy-efficiency levels for energy-using appliances. For example, the United States in 1987 set requirements for residential appliances and in 1992 extended standards to many commercial building appliances (U.S. Congress, OTA, 1992a). The European Community (EC) is considering standards for residential appliances (Lebot *et al.*, 1992; GEA, 1993).

Appliance standards eliminate the least-efficient new appliances by setting minimum energy-efficiency levels for new units. In the United States, appliance efficiency standards already enacted are projected to reduce electricity needs by 22 GW from 1990 to 2015 (Levine *et al.*, 1994).

### 22.5.1.4. Utility Regulation

Energy production, conversion (such as coal into electricity), and transportation for use in human settlements is dominated by government-operated or government-regulated entities because of the large capital requirements of energy supply systems, the importance of these systems to national security, and the natural monopoly status of many energy-distribution systems. For energy used in buildings (predominantly electricity and natural gas), service typically is provided by government-owned or regulated utilities.

In the past, these utilities viewed their role as providing dependable electric and gas supplies at a reasonable cost; they were not involved in how the energy was used. In recent years, however, uncertainty over future demand, plant siting constraints, environmental regulations, and other concerns have put increasing pressure on utilities to better plan their future capacity needs. One result of these forces is the emergence of a concept of utility planning called integrated resource planning (IRP). IRP has been an especially important aspect of utility planning in the United States during the past decade.

A basic tenet of IRP is that consumers do not require energy *per se* but rather energy services (e.g., lighting, heating, and cooling) and are therefore best served if these services are provided at the lowest overall cost. For example, it may be less expensive for a utility to install energy-efficient lights in offices than to build a new power plant to meet the demand of less-efficient lights. The service provided is the same, but the overall cost to provide it may be lower. IRP is the process of evaluating demand and supply options together to determine how to meet energy-service needs at the lowest cost.

Beginning in the late 1980s, changes in utility regulation in the United States to promote or require utilities to perform IRP led many utilities to invest in energy efficiency rather than in new energy supplies (Krause and Eto, 1988). These regulatory changes included limiting disincentives for efficiency—for example, by decoupling revenues from sales—and providing positive incentives for efficiency. In response to these changes,

in 1992 U.S. utilities invested $2.36 billion in demand-side management (DSM) programs—which include energy efficiency as well as peak shifting, peak reduction, and other activities intended to affect the timing or amount of customer energy use (Hirst, 1994). This investment was directed at a wide range of programs, including rebates to utility customers for the purchase of energy-efficiency measures, information programs providing audits and technical assistance, research and development, and funds for energy-service companies that bid against one another to provide energy-efficiency measures to customers (who typically pay a portion of the costs of the demand-side measures).

By one estimate, utility-run DSM programs in the United States led to national reductions in electricity peak demand of 3.7 to 4.2% from 1988 to 1990—about 20 GW of summer on-peak demand (EPRI, 1990). The cost-effectiveness of these investments is somewhat uncertain. A recent analysis of the costs and measured energy savings of 20 utility DSM programs for lighting, representing a total investment of $250 million, estimates the cost of the avoided electricity at 4.7 ± 1.9¢/kWh, compared with 6.9¢/kWh for average current U.S. electricity prices (Eto *et al*., 1994). In many cases, DSM is less expensive than traditional supply-side options, even in markets such as the United States in which considerable effort has been undertaken by means other than utility programs to increase energy efficiency.

More recently, forces that are leading to deregulation of the utility industry in the United States have reduced U.S. utilities' interest in promoting DSM. The future of large-scale utility DSM programs in the United States is much less certain as a result of possible regulatory changes, although various approaches have been proposed to continue such activities even in a much more deregulated environment. Because the United States has been a leader in this area, many other countries are closely watching these developments, and their own efforts are likely to be influenced by the evolution of utility DSM in the United States.

### 22.5.1.5. Research and Development

Research and development (R&D) is the process that generates and refines new energy-efficient technologies. In general, only large industries and governments have the resources and interest to conduct R&D. The building industry, in contrast, is highly fragmented. For example, single-family residential construction firms in the United States alone number more than 90,000 (U.S. Congress, OTA, 1992a). This fragmentation makes it difficult for the industry to pool its resources to conduct R&D.

Government-supported R&D has played a key role in developing and commercializing energy-efficient technologies. Low-e windows, electronic ballasts, and high-efficiency refrigerator compressors are examples of widely used technologies whose origins can be traced to public-sector funding of research. Maintaining public support for energy-efficiency R&D (with effective mechanisms to weed out unsuccessful

projects and avoid duplication of private investment) will help ensure the availability of the next generation of energy-efficient technologies.

Much of the R&D in industrialized countries is directly applicable to developing countries. Yet there are problems specific to developing countries that do not exist or are not central to industrialized countries. Examples include house design and construction in hot, humid climates for poor people; energy embodied in house construction, which often is greater than the energy used during house operation; and improved fuelwood and kerosene stoves. While researchers in industrialized countries can contribute to these tasks, also needed is an R&D infrastructure based in developing countries, as well as collaboration among different developing countries that share similar problems. Examples of such collaborative efforts include the Foundation for Woodstove Dissemination (based in Nairobi, with regional focal points in various countries) and the International Energy Initiative (with principal offices in Bangalore and São Paulo).

### 22.5.1.6. Information Programs

Energy information can be imparted in many forms—including labels and rating systems, demonstration programs, energy audits, and workshops. For example, in the United States and Australia, all major energy-using appliances carry energy labels showing estimated annual energy consumption (IEA, 1993).

Evidence is growing that information programs by themselves have only limited effects on behavior or on energy use. One review concludes that "informational programs are not sufficient to induce individuals to engage in resource conserving behaviors" (Katzev and Johnson, 1987). Information programs are built on the premise that people will generally do what is cost-effective if they know what specific opportunities exist. However, consumers and other decisionmakers often define "cost-effective" differently than do analysts, and consumers often lack the incentive or motivation to use energy-efficient technologies. In such cases, information alone will have little effect. Information programs generally are more effective if they are targeted at specific people and specific behaviors; combined with other programs, such as incentives; and evaluated regularly, with the results of these evaluations used to improve the program.

Programs that establish the performance of energy-using equipment often are prerequisites for other policy approaches. Other programs, such as appliance standards, rebates, and building codes, depend on a credible energy rating.

A new type of information program combines site-specific technical information, public commitment, and positive feedback to encourage cost-effective lighting retrofits. The Green Lights program, run by the U.S. EPA, has had considerable success in encouraging large corporations to undertake comprehensive lighting retrofits. This voluntary program offers

participating companies positive publicity and free technical support. In exchange, the participants must agree to implement all cost-effective lighting retrofits. By one estimate, this program had reduced electricity demand by 70 MW as of December 1993 (U.S. EPA, 1994). A similar program exists for personal computers: Those meeting the EPA's energy efficiency standard are allowed to be labeled as "Energy Stars" (see Section 22.4.2.4). This is seen as a marketing advantage, and many manufacturers have increased the efficiency of their computers to meet the voluntary standard.

### 22.5.1.7. Special Policy Options for Developing Countries

Besides policy options shared with industrialized countries, developing countries require training, institution-building, capital, and promotion of rural development to increase energy efficiency in buildings (Munasinghe, 1991).

Training efforts need to address all major elements of energy efficiency and related technologies for reducing GHG emissions, including in-depth studies in engineering, economics, public policy, and management. The training needs to be both theoretical and practical. Much of the training will probably best be done within the developing countries, but substantial assistance from industrialized countries in creating and carrying out training courses will be necessary.

In some cases, new institutions (such as the energy-efficiency centers that have been created in Russia, Eastern Europe, and China) will be needed to coordinate a broad range of activities. Such institutions are needed to make certain that energy efficiency and alternative energy investments are treated equally with traditional supply investments and make it possible to "bundle" a large number of demand-side investments into a large investment so that they can attract capital (Gadgil and Sastry, 1992).

Capital needs to be made available for energy-efficiency projects. This availability of capital depends in large measure on the success of training and institution-building—which will enable developing countries to identify viable projects for investment—as well as on the financial climate of the developing nation. The multinational development banks and the Global Environment Facility—a joint program of the United Nations Development Programme, The World Bank, and the United Nations Environment Programme—can assist greatly in providing large-scale "demonstrations" of energy-efficiency projects in developing countries.

Effective rural development will reduce both migration to urban areas and population growth. Examples of important thrusts for rural development include provision of electricity to all households; improved fuelwood stoves, as well as stoves and fuel supply for kerosene and alcohol; adequate water supply and sewage; adequately matched end-use devices and energy sources (e.g., kerosene stoves but not lamps; biogas for electricity generation but not gas lamps; fluorescent, not incandescent, lamps) (Dutt, 1992); identification of leapfrogging opportunities in appliances (e.g., refrigerators) and other energy-using equipment; and use of high-rate anaerobic processes for wastewater treatment.

There are efforts underway through international organizations, overseas development programs, and developing countries using their own resources (China, Thailand, and Brazil are notable examples) that represent an important start in creating the infrastructure for much more efficient use of energy in developing nations.

### 22.5.1.8. Summary/Conclusions

Table 22-2 summarizes key characteristics of the options discussed in Section 22.5.1. In addition, several lessons have

*Table 22-2:* Key characteristics of selected policy options.

| Policy | Can Affect New Building Construction | Can Affect Existing Building Retrofit | Appliance Selection | Energy Savings Potential[1] | Direct Cost to Government |
|---|---|---|---|---|---|
| Energy Taxes | Yes | Yes | Yes | High | Negative |
| $ Incentives | Yes | Yes | Yes | High | High[2] |
| Building Codes | Yes | (3) | (4) | Medium | Low |
| Appliance Standards | No | No | Yes | High | Low |
| IRP | Yes | Yes | Yes | High | Low |
| R&D | (5) | (5) | No | Variable | Medium |
| Information Programs | Yes | Yes | Yes | Low | Low |

[1]Energy savings will, of course, vary; this table shows *potential*, and assumes aggressive implementation (e.g., high energy taxes).
[2]If an incentive is offered by a utility, the direct cost is borne by the utility (which is, in many cases, run by the government).
[3]Some cities, such as San Francisco, require existing buildings to meet energy codes as a condition of change in ownership.
[4]Most code requirements apply to the building shell only; however, some codes apply to appliances as well.
[5]R&D effects are long-term.

been learned from past experience that apply to all options, as follows:

- All policies should be evaluated frequently to determine their effectiveness.
- Many policies work in combination with others. Mutually reinforcing regulatory, information, incentive, and other programs offer the best hope for achieving significant portions of the cost-effective energy-efficiency potential.
- Finally, policy experimentation should be encouraged on a small scale. The process of experimenting, evaluating, improving, and expanding can result in policies that will successfully implement the wealth of technologies now available for reducing the emissions of gases contributing to climate change.

### 22.5.2. Heat Islands

Afforestation efforts or purchases of forested lands to protect them from deforestation have been undertaken to sequester carbon. However, no systematic and comprehensive effort has been made to plant trees or increase the reflectivity of urban areas to mitigate the impact of heat islands. For such an effort to be undertaken, the following steps need to be carried out:

- Create test procedures, ratings, and labels for cool materials.
- Assemble a database on all measures to reduce urban heat islands.
- Incorporate cool roofs and shade trees into building codes in climates where their impact is beneficial.
- Offer utility rebates or other incentives to beat the standards.
- Establish demonstration centers in which the concept of community-wide planting of trees and increased reflectivity is demonstrated to reduce cooling requirements.

### 22.5.3. Methane Reduction

An awareness of the economics of alternatives for methane recovery and use is often lacking among government officials and potential developers in various countries. Experience with techniques for methane recovery and use for power generation also is lacking. Appropriate demonstration projects can help overcome this problem.

Often, many groups are responsible for different aspects of waste management. Any one weakness in the chain of responsibility can cause failures in the overall waste-management system. Furthermore, different groups generally are responsible for energy generation, fertilizer supply, and waste management. In many places, laws and regulations about waste disposal are either unclear, not enforced, or not supportive of measures to collect methane and use it productively.

These problems have been overcome in some communities by organizing joint management groups for waste management, fertilizer supply, and energy generation (U.S. EPA, 1993b). This single entity, which can be private or public, needs to have the capability and authority to deal with these matters simultaneously.

In many developing countries, projects with higher initial costs that are otherwise profitable are not undertaken because of lack of capital for investment (often resulting from uncertain financial institutions that make capital difficult to attract). Also, as noted, many developing countries have highly subsidized energy prices that make methane recovery not cost-effective. Financing of methane recovery (such as that carried out in China under the auspices of the Global Environment Facility) can help solve these problems, as can the deregulation of energy prices.

## 22.6.  Scenarios

The scenarios discussed below focus on GHG emissions from energy consumption in buildings because buildings represent 75% of the emissions treated in this chapter. It is likely, however, that two of the other three sources of GHG emissions from human settlements—methane from landfills and wastewater—could be controlled as much as $CO_2$ emissions resulting from energy use in buildings. The third source, PICs from burning of biomass in cookstoves, is likely to be largely eliminated over the long term as biomass is converted into or replaced by modern fuel forms.

We focus on two time periods: the intermediate term (2025) and the long term (2075 to 2100). There has been sufficient work on the development of scenarios to make observations regarding the intermediate time period. Comments about the long term are necessarily more speculative.

### 22.6.1.  Historical Perspective

Table 22-3 shows total energy use and $CO_2$ emissions attributed to residential and commercial buildings. This information is presented for the years 1973, 1983, and 1990 for three major regions of the world (OECD, FSU/EE, and developing countries) and for the world as a whole. Table 22-4 is derived from the data in Table 22-3 and shows the annual growth rates of energy consumption and $CO_2$ emissions for three time periods: 1973 to 1983, 1983 to 1990, and 1973 to 1990. The key points follow:

- Average energy growth in buildings between 1973 and 1990 worldwide was 2.5% per year, compared with an average increase in energy use in all sectors of 2.7% per year during the same period.
- Average annual increase in $CO_2$ emissions was 1.2% per year. Thus, the carbon emissions increased an average of 1.3% less per year than buildings energy use between 1973 and 1990, indicating an improvement in carbon intensity (carbon emissions per unit of buildings energy use).

**Table 22-3:** *Primary energy use and $CO_2$ emissions from energy use in residential and commercial buildings (1973–1990).[1]*

| | Residential | | Commercial | | Total | |
|---|---|---|---|---|---|---|
| | Energy (EJ) | Emissions (Mt C) | Energy (EJ) | Emissions (Mt C) | Energy (EJ) | Emissions (Mt C) |
| **OECD** | | | | | | |
| 1973 | 31 | 694 | 17 | 347 | 48 | 1041 |
| 1983 | 33 | 626 | 20 | 355 | 53 | 981 |
| 1990 | 36 | 666 | 25 | 407 | 61 | 1073 |
| **FSU/EE** | | | | | | |
| 1973 | 9 | 133 | 3 | 44 | 12 | 177 |
| 1983 | 14 | 197 | 6 | 66 | 20 | 263 |
| 1990 | 15 | 225 | 8 | 75 | 23 | 300 |
| **Developing Countries** | | | | | | |
| 1973 | 6 | 109 | 2 | 47 | 7 | 156 |
| 1983 | 11 | 154 | 3 | 66 | 13 | 220 |
| 1990 | 15 | 225 | 4 | 97 | 19 | 322 |
| **World** | | | | | | |
| 1973 | 45 | 936 | 22 | 438 | 67 | 1374 |
| 1983 | 57 | 977 | 29 | 487 | 86 | 1464 |
| 1990 | 66 | 1116 | 37 | 579 | 103 | 1695 |

[1] Primary energy data are from WEC (1995) and supporting documentation for that report. Residential emissions data for industrialized countries are based on extrapolation of data for nine countries (Schienbaum and Schipper, 1993); commercial emissions data for industrialized countries are based on unpublished energy use data for the same nine countries collated from national sources by Lawrence Berkeley Laboratory. Emissions for developing countries are based on extrapolation of energy use data for 16 developing countries based on unpublished energy use data collated from national sources by Lawrence Berkeley Laboratory. Emissions for FSU/EE are based on data for the former Soviet Union (Cooper, 1993) and Poland (Meyers *et al.*, 1993b).

- In the OECD, there was almost no increase in carbon emissions from buildings energy use between 1973 and 1990 (0.2 % per year); however, the annual growth of carbon emissions from energy consumption went from -0.6% (1973 to 1983) to +1.3% (1983 to 1990).
- In the FSU/EE, energy use in buildings increased relatively steadily from 1973 to 1990; however, the rate of growth in carbon emissions from energy used in buildings declined from 4.0% per year (1973 to 1983) to 1.9% per year (1983 to 1990). After 1990, energy use in the region declined because of the economic disintegration experienced as an aftermath of the breakup of the Soviet Union.
- The average increase in energy use in buildings in developing countries from 1973 to 1990 was 5.8%; the annual increase in carbon emissions was 4.4%.
- Overall, residential buildings use about twice as much energy and are responsible for about twice the carbon emissions as commercial buildings. However, annual energy use in commercial buildings has grown over 35% faster between 1973 and 1990, and their annual carbon emissions have grown 60% faster.

### 22.6.2. *The Intermediate Term (2020–2025)*

None of the well-known global energy scenarios has been devoted only to residential and commercial buildings for the period 2020 to 2025.[11] However, many scenarios have treated all sectors in terms of both energy and $CO_2$ emissions (IPCC, 1995). We review the following cases: (1) IPCC's 1992 ISb scenario (Pepper *et al.,* 1992); (2) the most recent World Energy Council (WEC) cases (WEC, 1993); and (3) a study for the Global Energy Efficiency Initiative (GEEI) (Levine *et al.,* 1991). We present total energy because these cases do not provide sufficient information to obtain energy used by buildings. We also present an estimate of energy use in buildings and associated $CO_2$ emissions that are roughly consistent with the three sets of scenarios.[12]

#### 22.6.2.1. Reference Cases

A comparison of the reference cases developed by these three groups reveals surprising similarities among them. The energy

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[11] A recent World Energy Council report, not yet widely distributed, provides detailed scenarios for residential and commercial buildings to 2020 (WEC, 1995).

[12] In all of the cases considered, energy in buildings approximately tracks total energy use, as best as can be determined from the information provided. Energy demand growth in residential and commercial buildings is somewhat above that of all end-use sectors for the developing countries and somewhat below that for the industrialized countries. Therefore, we multiply the results for all end-use sectors by 0.30 to obtain estimates of energy use and emissions associated with residential and commercial buildings.

***Table 22-4:*** *Annual average growth rates (%) of primary energy use and $CO_2$ emissions from energy use in residential and commercial buildings (1973–1990).*

|              | **Energy** | **Emissions** |
|--------------|:----------:|:-------------:|
| **OECD**     |            |               |
| 1973–1983    | 1.0        | -0.6          |
| 1983–1990    | 2.0        | 1.3           |
| *1973–1990*  | *1.4*      | *0.2*         |
| **FSU/EE**   |            |               |
| 1973–1983    | 5.3        | 4.0           |
| 1983–1990    | 2.2        | 1.9           |
| *1973–1990*  | *4.0*      | *3.2*         |
| **LDC**      |            |               |
| 1973–1983    | 6.1        | 3.5           |
| 1983–1990    | 5.4        | 5.6           |
| *1973–1990*  | *5.8*      | *4.4*         |
| **World**    |            |               |
| 1973–1983    | 2.5        | 0.6           |
| 1983–1990    | 2.6        | 2.1           |
| *1973–1990*  | *2.5*      | *1.2*         |

demand in 2025 is between 1.65 and 2.05 times that in 1990, and the average annual growth rate is between 1.5 and 2.0% per year. All three groups produce a 2025 reference case with energy use very nearly double 1990 levels, corresponding to an annual growth rate of 1.9 to 2.0%.

On the one hand, this close agreement among the different groups on an expected reference case for energy in the year 2025 is surprising because of the tremendous number of unknowns about future energy demand. As noted in Section 24.3, a large number of factors influence energy demand growth. The average annual growth in energy demand since 1973 has been about 2.4% per year (with energy in buildings growing at 2.1% per year during the period). Thus, the similarity among the scenarios reveals that the best guess about the future is that it will be much like the past. In this case, it appears that analysts implicitly assume that the next three decades will be much like the two decades since the oil embargo.

The WEC case shows almost the entire energy growth during the period occurring in the developing world. The IPCC and GEEI cases have about 70% of energy growth happening in the developing world. In spite of this concentration of growth, energy per capita in the developing world in all of the reference cases remains a small fraction of that in the industrialized countries. For example, in IPCC reference cases IS92a and IS92b, energy per capita in developing countries grows from 10% of that of industrialized countries in 1990 to 17.5% in 2025.

### 22.6.2.2. Efficiency Cases

WEC provides two energy-efficiency policy cases. One assumes that very significant efforts are made throughout the world to achieve energy efficiency. This case results in a reduction in energy growth by 0.6% per year from the reference case. The other is an extremely high-efficiency case with a "rate of reduction in energy intensity far in excess of anything achieved historically" and a "very low increase in energy demand in the developing countries." In this second case, energy growth diminishes an additional 0.6% per year, resulting in an increase in energy demand of 0.9% per year. In this case, the energy consumption in the OECD declines 25%, that in the former Soviet Union and Eastern Europe remains about the same as in 1990, and that in the developing world doubles.

The GEEI energy-efficiency case reduces annual energy demand growth by 0.73%, yielding an annual increase of 1.1% per year. This case assumes a very significant push for energy efficiency in both the industrialized and the developing countries. In the GEEI efficiency case, energy demand in the OECD is essentially unchanged between the present and 2025, whereas energy demand in the developing world almost doubles.

IPCC does not provide any policy cases. However, the U.S. Environmental Protection Agency produced policy scenarios that are useful in a general way in indicating global energy-efficiency opportunities for 2025 and beyond (U.S. EPA, 1990). The Rapidly Changing World scenarios most nearly approximate the WEC and GEEI cases considered above. Policies promoting energy efficiency reduce the annual growth rate of energy by 0.5% per year, from 1.95 to 1.43% annually, from the present to 2025. In the other major pair of reference and policy cases analyzed by EPA, the Slowly Changing World scenarios, energy demand was reduced by 0.41% per year, but from a much lower growth rate of 1.07% per year.

Although there is tremendous uncertainty about the future demand for energy (IPCC, 1995), the reference case of key analyses hovers around 2% per year energy growth for this time period. Under these assumptions (business much as it has been during the past 2 decades), with considerable emphasis on energy efficiency in these reference cases and most of the energy growth in the developing world, aggressive policies to increase energy efficiency could reduce annual demand growth by 0.5 to 1.0%.

What would be required to maintain carbon emissions from energy at current levels between 1990 and 2025? These studies suggest that, in a reference case with energy demand growing at an average of 2% per year during the period, strong policies to promote energy efficiency could be responsible for about 30% to 60% of the effort needed to achieve zero growth in carbon emissions from energy.[13] The remaining 40 to 70% reductions in carbon emissions would need to come from fuel switching—from fuels of higher to those of lower or zero carbon intensity (i.e., greater use of natural gas, renewable energy sources, or nuclear energy)—to achieve 1990 carbon emissions

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[13] A 2% annual energy growth for 35 years will double energy demand; a 1.5% annual growth over this period results in a 68% increase in energy demand; a 1% annual growth increases energy demand by 41%.

in 2020 under the reference-case assumptions. Another way of saying this is that aggressive policy to promote energy efficiency over the next three to four decades could, under typical reference-case assumptions, contribute about half of the effort needed to maintain carbon emissions from energy use at current levels.

### 22.6.3. The Long Term (2025–2100)

Scenarios for energy demand to the year 2100 vary dramatically (IPCC, 1995). Carbon emissions vary much more than energy consumption because energy of widely varying carbon contents can be used. In reviewing a large number of global scenarios for the year 2100, the IPCC (1995) notes that energy intensity varies by less than a factor of 3. More specifically, the different scenarios calculate (or assume) an energy intensity index varying from about 0.2 to 0.55 for 2100, whereas the index is 1.0 today (the index is a measure of energy use per unit gross world product).

Thus, in this very aggregate view, if gross world product grows to about 4.5 times 2025 levels by 2100 (as assumed in IPCC IS92a and b), then global energy use by 2100 might be expected to grow by a factor of about two to three times that of 2025. Higher and lower growth rates of gross world product per capita and of population would increase or decrease energy growth in this period accordingly. The most extreme of the six IPCC cases has gross world product per capita growing somewhat more than twice and less than half the size of the base case in 2100; population projections also show significant variations by 2100.

This review of long-term scenarios suggests that one might expect energy use in 2100 to be about two to three times that of 2025 if the world economy grows at a modest rate (e.g., 2%) during the period and population growth declines to about 0.4% per year. Lower economic and population growth could significantly lower the energy projection, and higher growth rates would increase it. We believe that this review of energy scenarios applies well to energy in buildings as well. Most long-term scenarios for energy show buildings using 30 to 35% of total energy, both at present and in the long term.

Goldemberg *et al.* (1987a, 1987b, 1988) describe end-use oriented strategies for industrialized countries that suggest ways in which per capita energy use can decline by substantial amounts. They also provide energy strategies for developing countries that increase per capita energy use to meet needed energy services and avoid inefficient energy uses. While the authors carry their analysis only to 2020, their ideas apply well to a longer term view in which major transformations in all energy-using stock will take place.

A low-energy future for buildings in 2100 could include the following:

- Virtual elimination of space heating in all climates by means of building shells with very high resistance to heat loss or gain, involving high-insulation walls, ceilings, and floors and triple-pane windows with transparent, heat-reflecting films; wide use of passive solar designs; and mass-produced components (walls, ceilings, etc.) with very low infiltration rates
- Reduced need for space cooling and dehumidification because of improved building design and use of passive cooling; provision of cooling and dehumidification by very high-efficiency systems; and use of low-resistance ducts and high-efficiency variable-speed motors for pumps
- Water heating that uses active solar systems combined with the use of waste heat from refrigerators
- Advanced lamp technology combined with lighting controls, task lighting, and greater use of natural light, reducing lighting energy requirements to 10 to 15% of today's levels
- A dramatic decline in refrigerator/freezers' energy use through the use of high insulating walls and doors, efficient compressors, advanced motors, and so forth. Energy use declines to 250 kWh/year by 2025. After 2025, entirely new ways of storing and cooling food could further reduce energy requirements.
- Residential and low-rise commercial buildings that become net producers of energy as roofs incorporate photovoltaic panels and small biofuel power plants provide backup electricity.

Such a future could result in long-term declines in residential energy use in the industrialized world and relatively modest added requirements in the developing world after 2025. Energy use in commercial buildings, on the other hand, will likely continue to increase much longer than in residential buildings.

One scenario for low energy use in residential and commercial buildings in 2100 has been developed by Lazarus *et al.* (1993). In this scenario, delivered energy use for residences in 2100 is very close to today's level.[14] Delivered energy for commercial buildings is triple today's level. All of this increase occurs in the developing world; delivered energy use in commercial buildings in the OECD declines from today's levels.

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[14] Primary energy is higher than today because of increasing electrification, brought about in part by the elimination of the use of fossil fuels in the scenario.

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